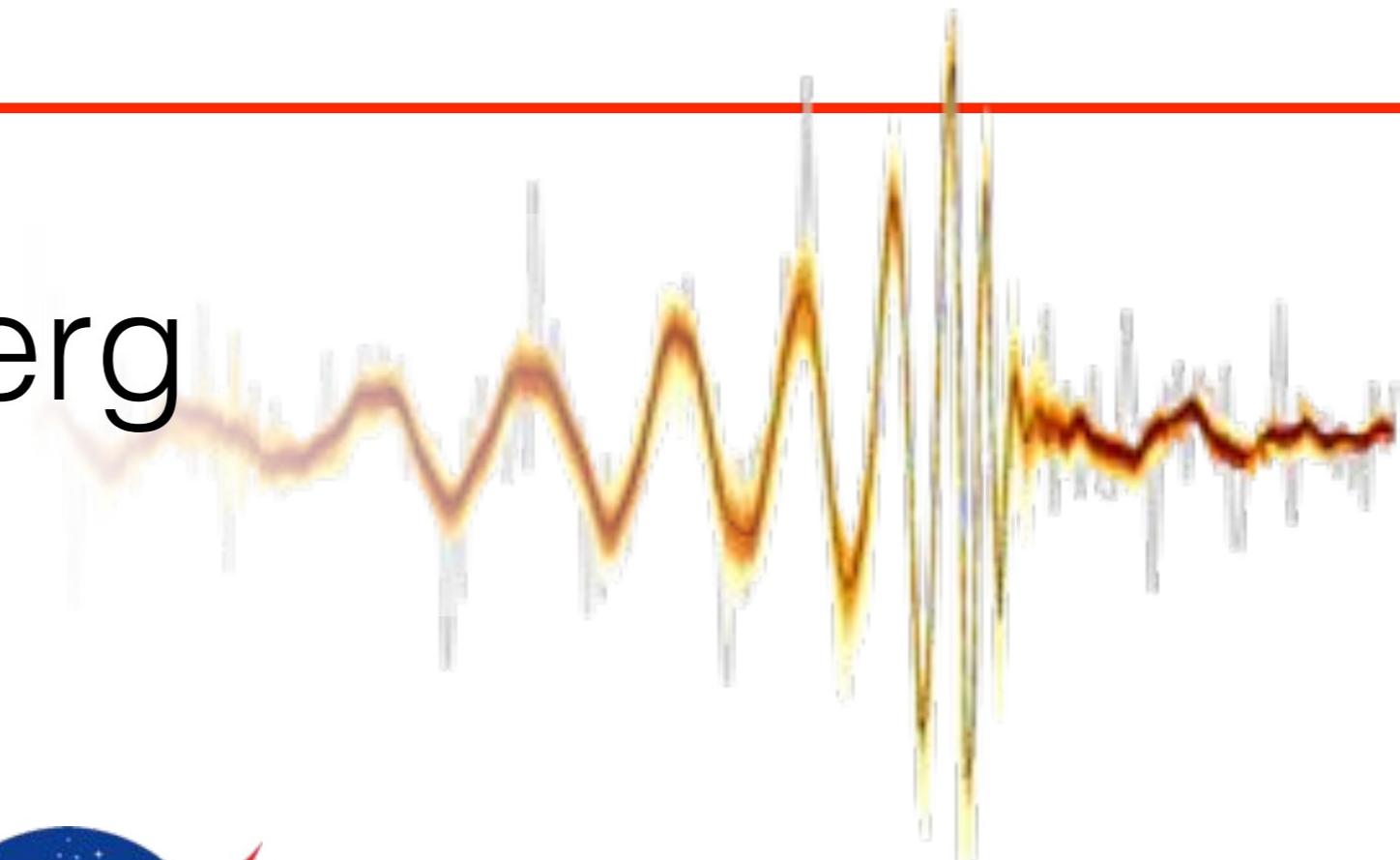
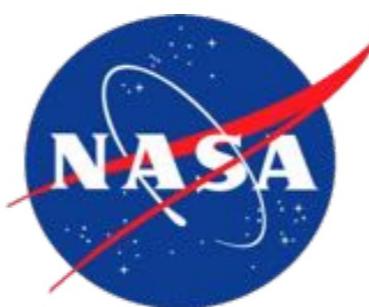


# Gravitational Wave Astronomy

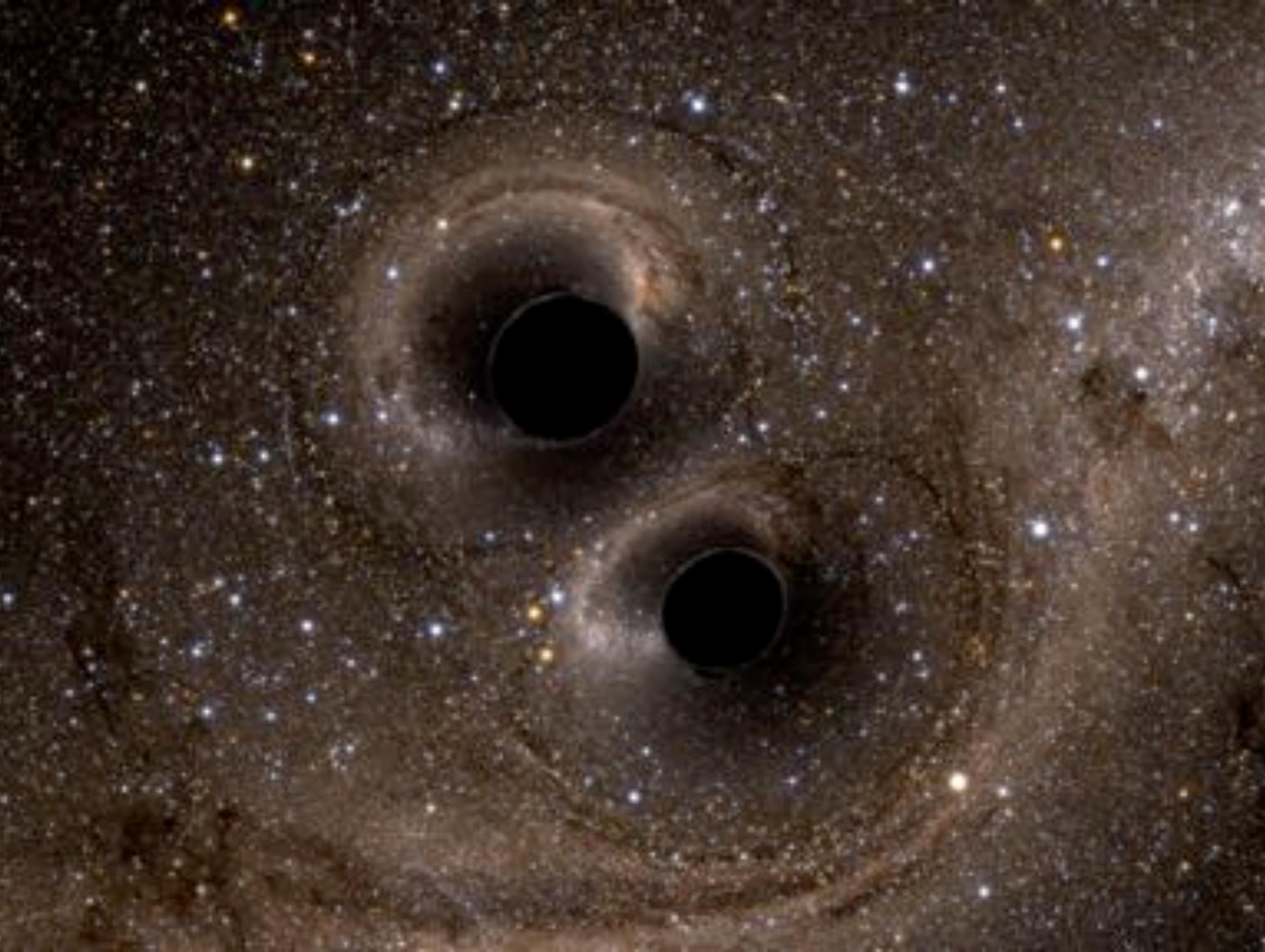
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Tyson B. Littenberg

NASA/Marshall Space Flight Center





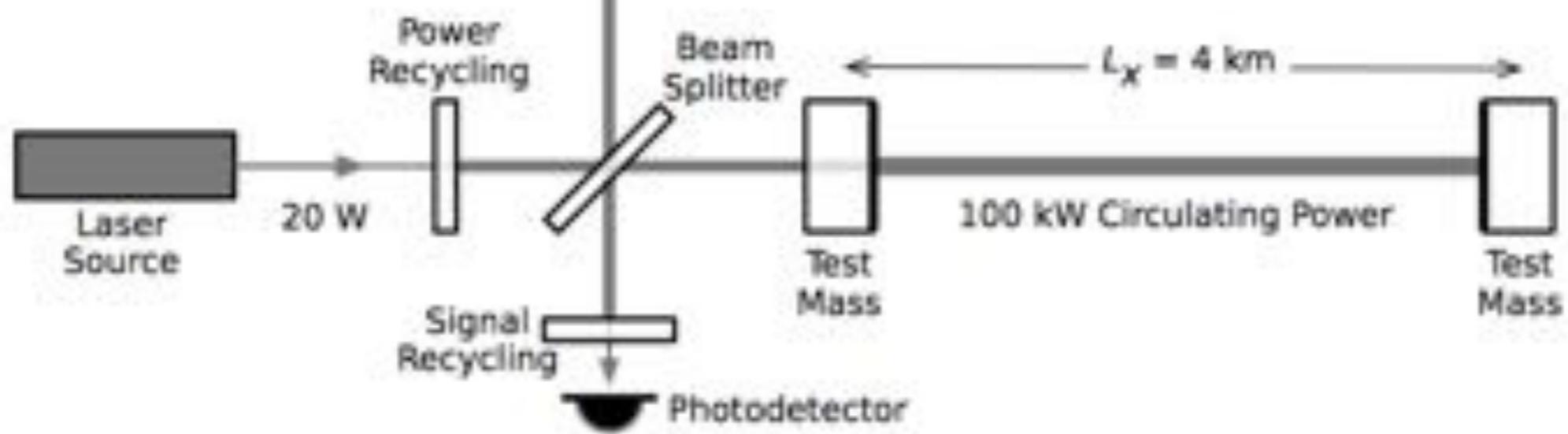
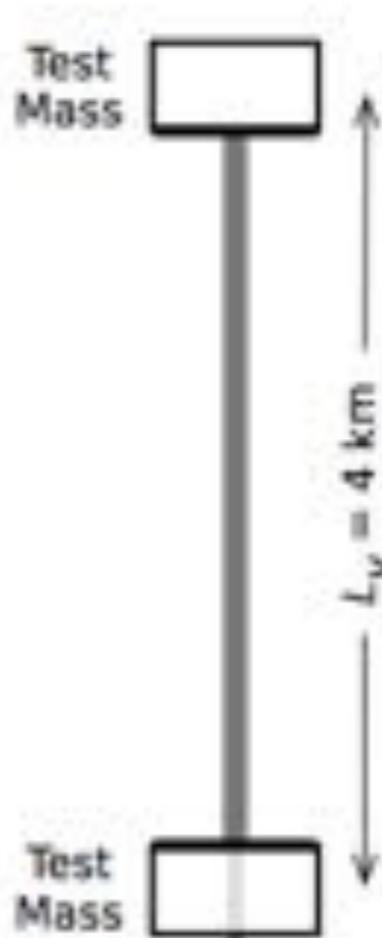






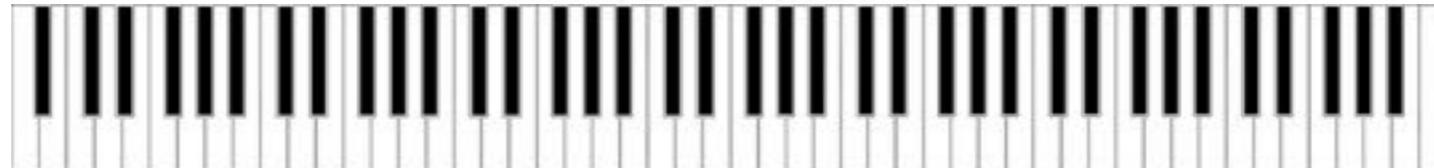
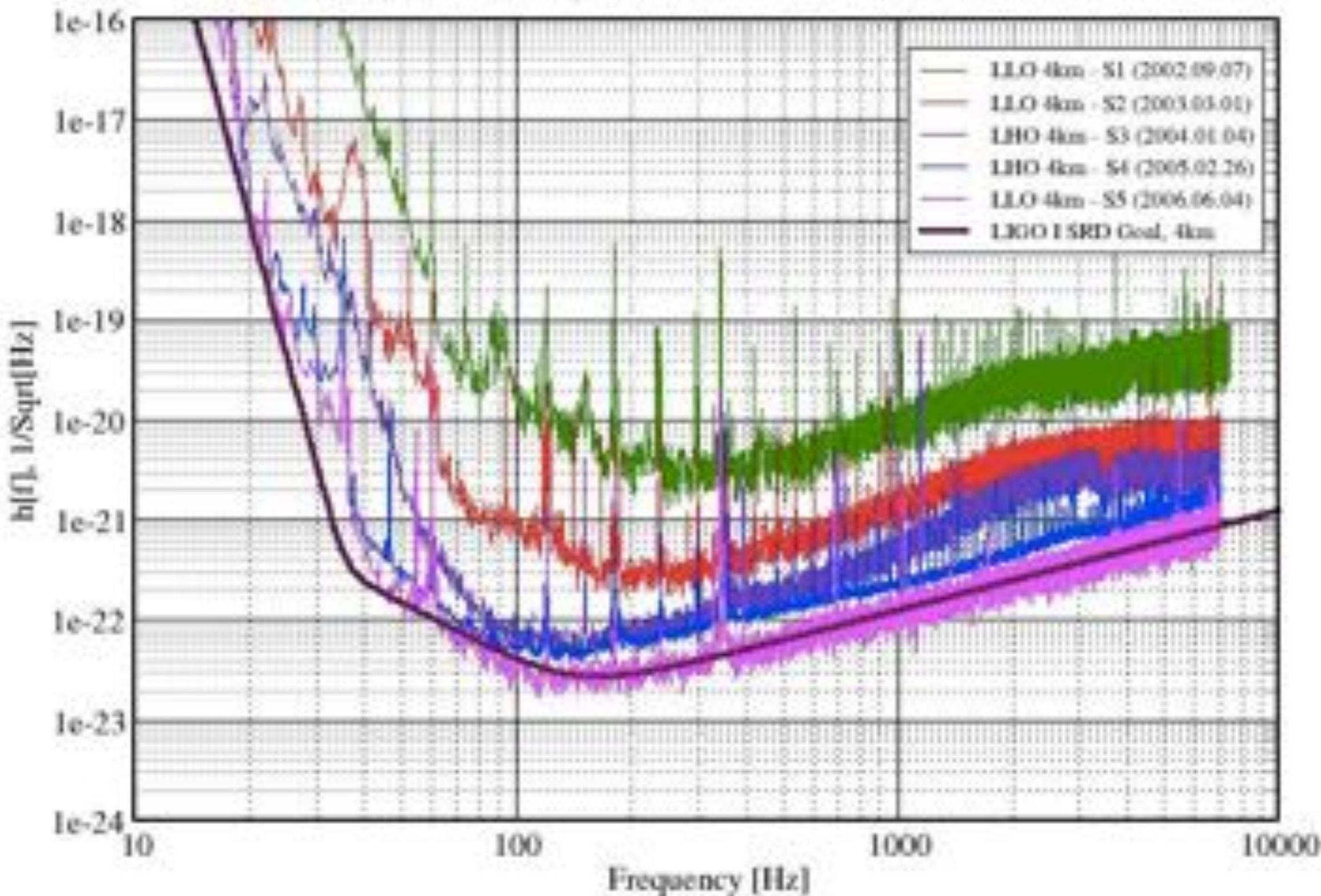


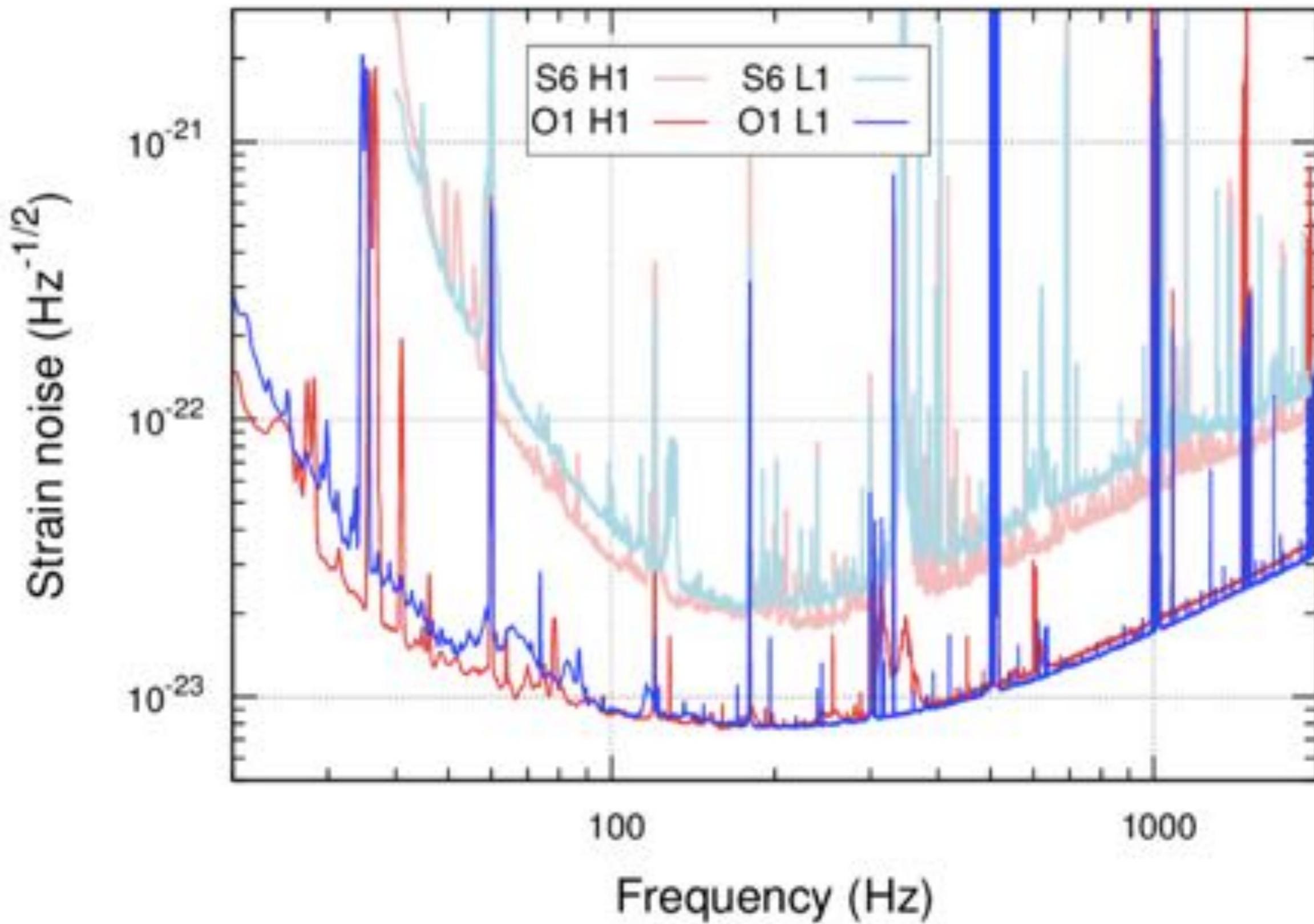
LASER  
INTERFEROMETER  
GRAVITATIONAL  
WAVE  
OBSERVATORY



# Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs    LIGO-G060009-02-Z

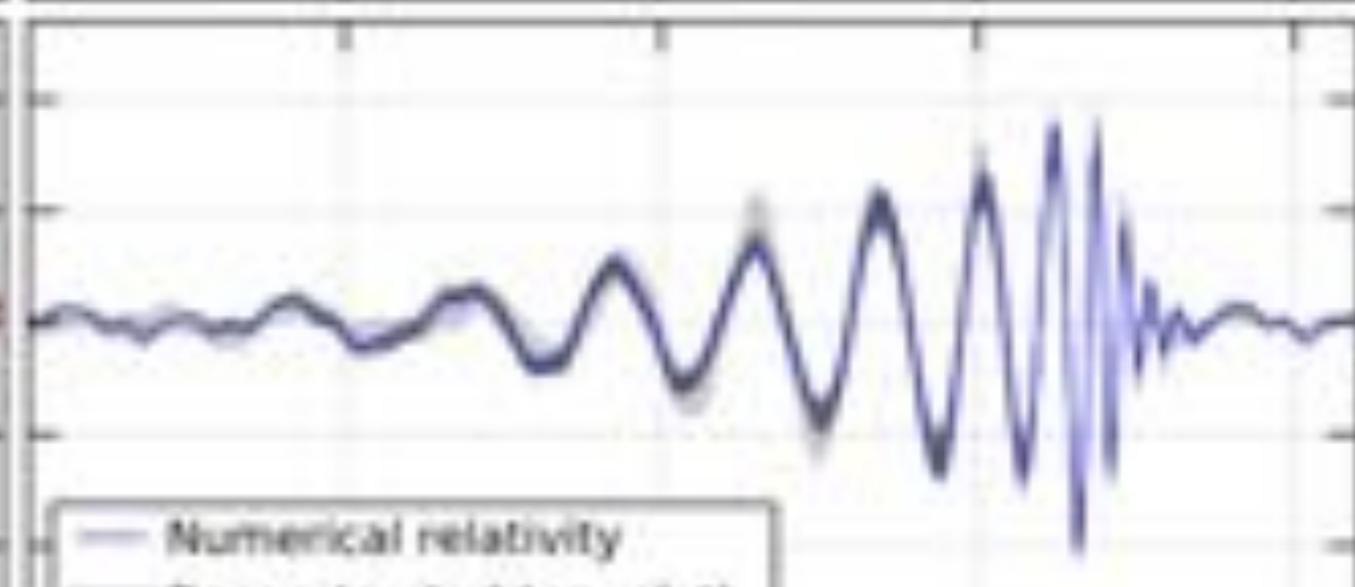
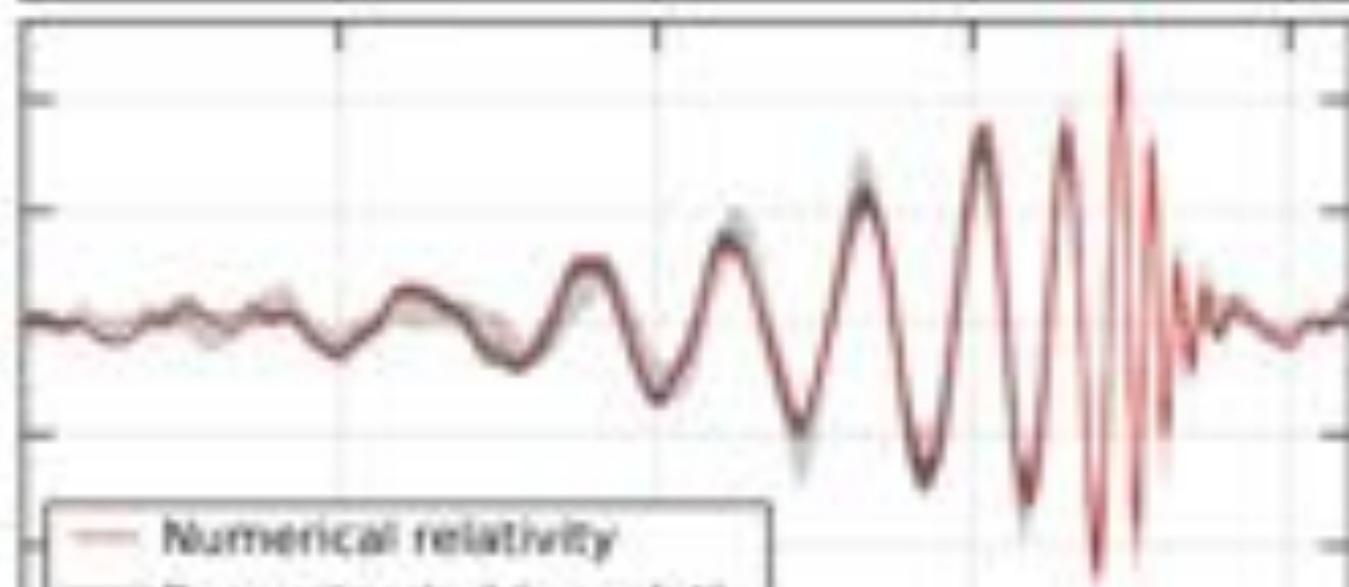
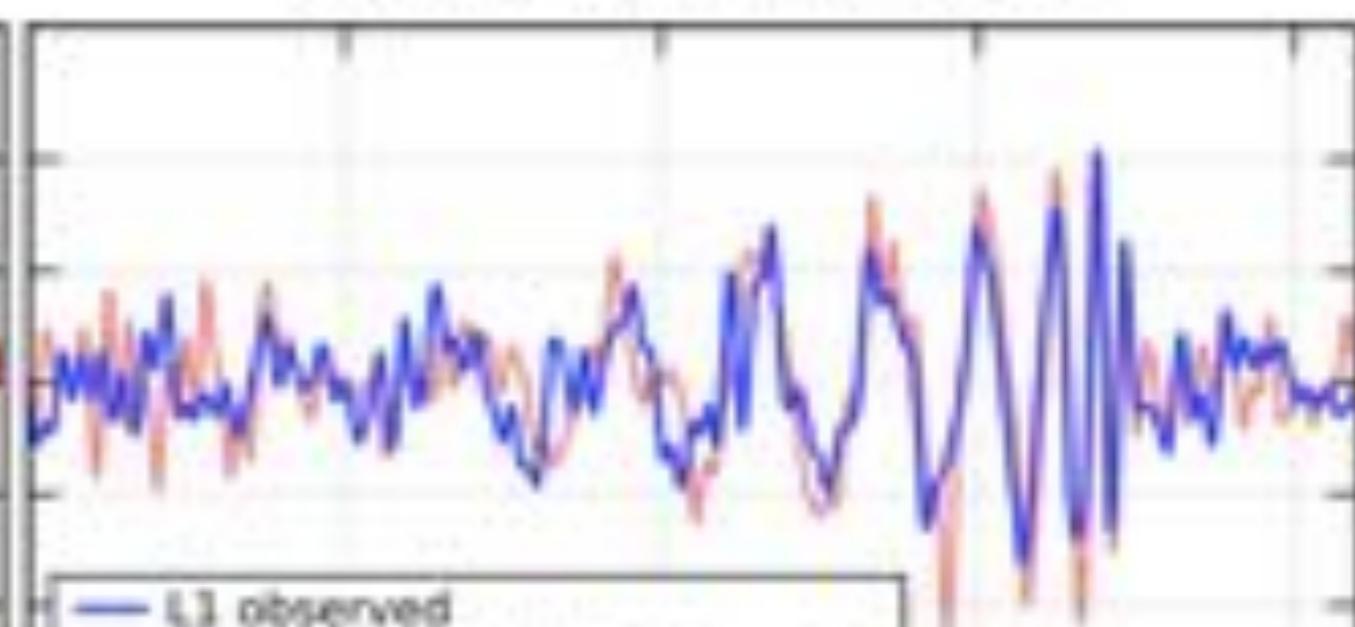
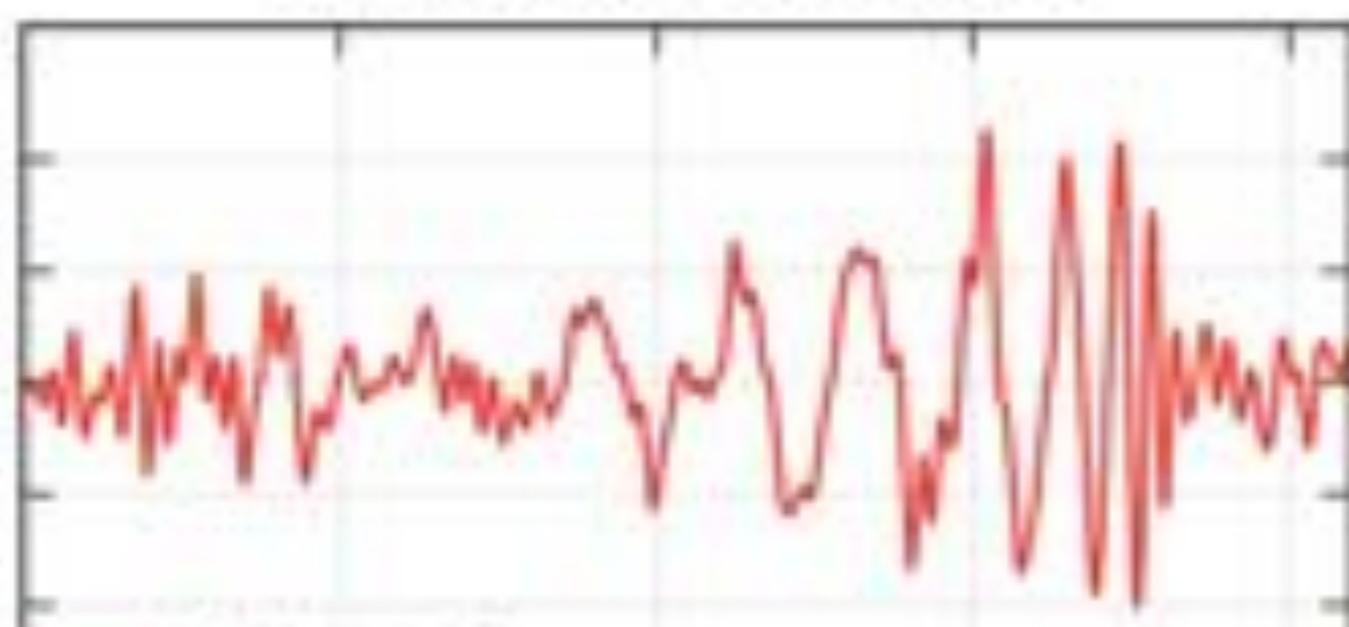






Hanford, Washington (H1)

Livingston, Louisiana (L1)



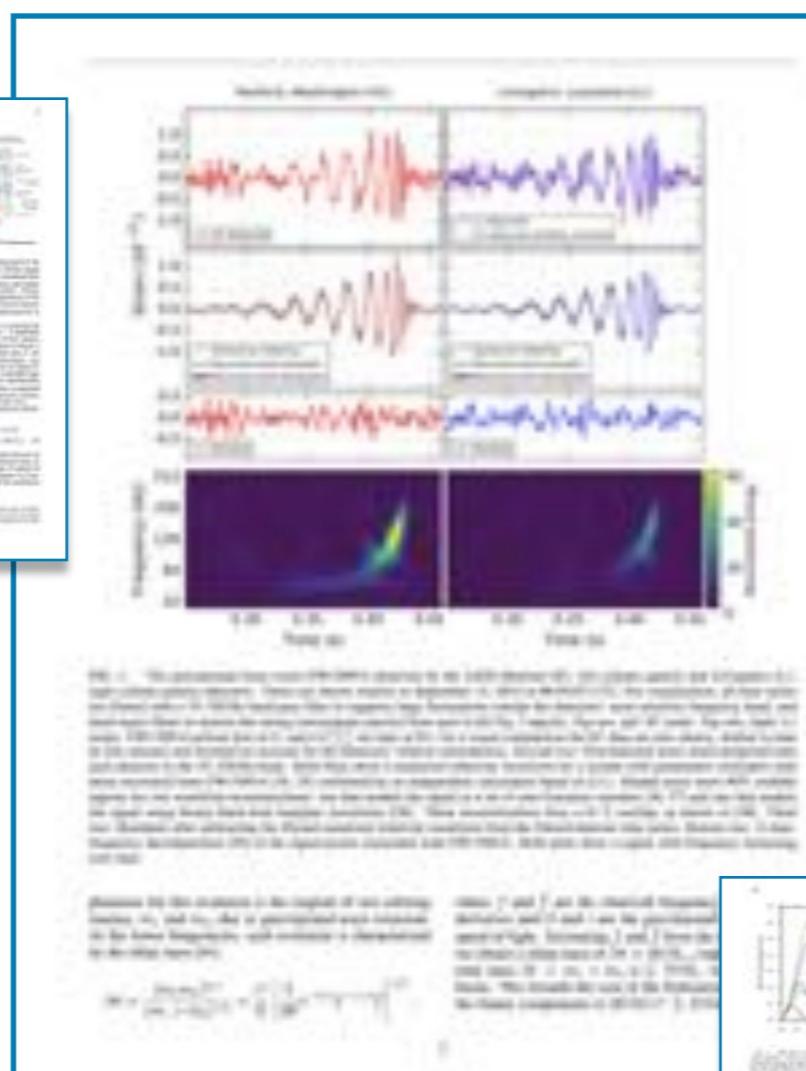
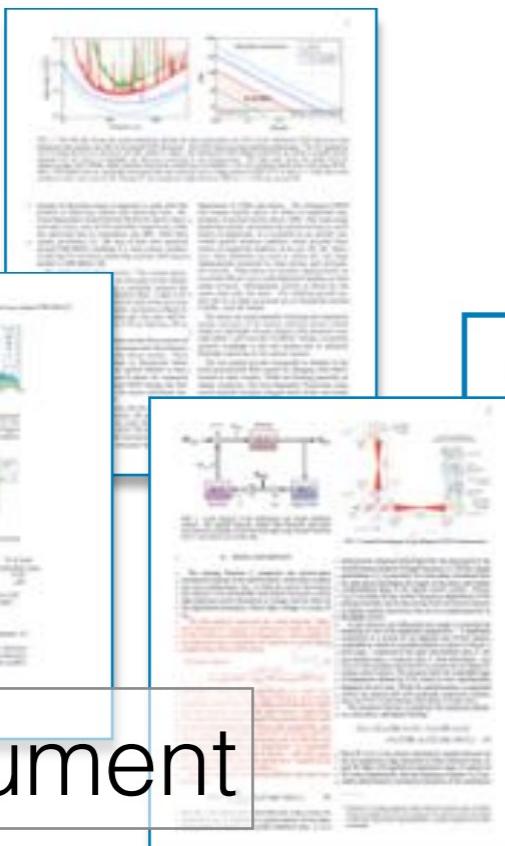
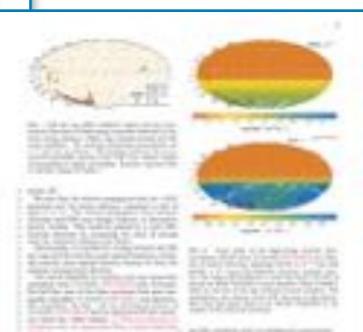
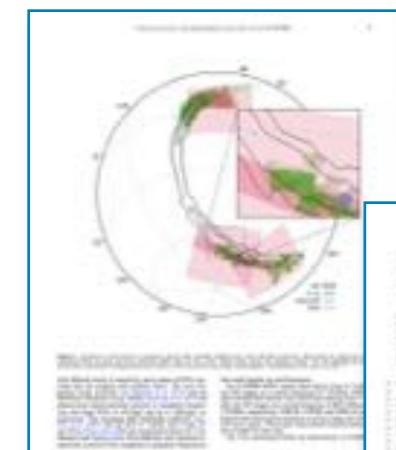
0.30 0.35 0.40 0.45

Time (s)

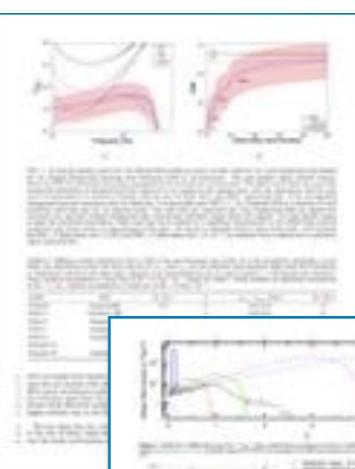
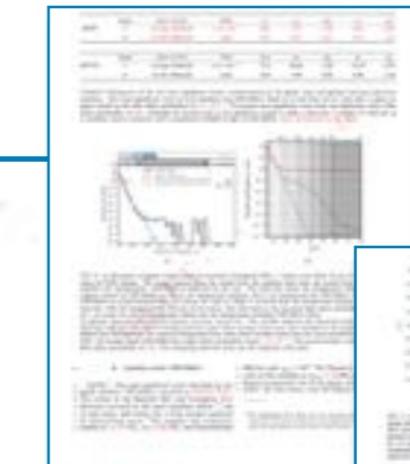
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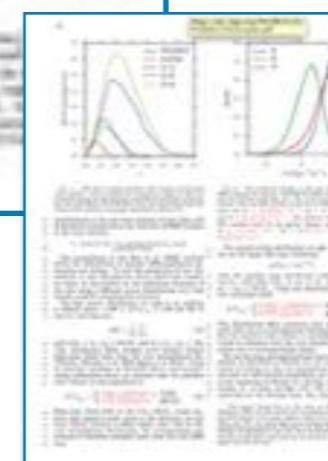
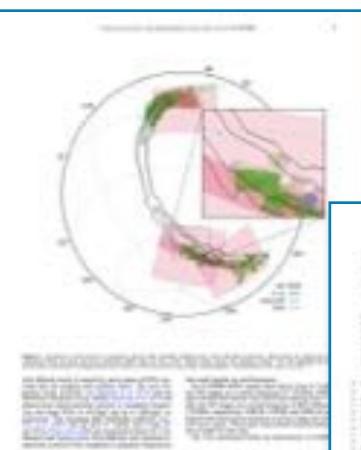
## Instrument



## Measurement



## Multimessenger



## Interpretation

The front page of The Bakersfield Californian features a large, dark, abstract photograph of water or waves at the top. Below it, the masthead "The Bakersfield Californian" is displayed in a large, serif font. A sub-headline "TUESDAY, JULY 15, 2014 • MIDDLETIER EDITION" is positioned below the masthead. To the right of the masthead, there's a small graphic of a person's head and shoulders. The main headline "MAKING WAVES" is written in large, bold, white letters across the middle of the page. To the right of the headline, there's a column of text: "Opponents accuse the city of trying to prevent construction of a new Los Angeles General Poetry Foundation facility." Below this text is a box containing the words "VIEW POLICY" and "BY JEFFREY L. ROBERTS". On the far right margin, there are several vertical columns of news headlines. At the bottom of the page, there's a horizontal advertisement for a car dealership with three cars shown and their prices: \$299, \$430, and \$1,099.

The image is a composite of two photographs. The top half shows a black hole with a bright accretion disk and a central singularity, set against a dark background. The bottom half shows two men in a courtroom; one man is seated at a desk with papers, and the other stands behind him. To the right of the main image is a vertical column of news headlines.

# The New York Times

The image shows the front page of the Santa Fe New Mexican newspaper. The masthead "SANTA FE NEW MEXICAN" is prominently displayed at the top in large, bold letters. Below the masthead is a large, colorful photograph of a woman. To the left of the main title, there's a smaller image of a person. The page features several news stories with accompanying images. One story about a council candidate discusses the future of the city. Another story is titled "With faint chirp, scientists prove Einstein correct" and includes an image of a black hole. There are also sections for "Perspective" and "Opinion". The overall layout is typical of a local newspaper with various columns and headings.

The image shows the front page of The Denver Post. The main headline reads "LISTENING TO A WINTERWONDERGRASS..." above "THE DENVER POST". Below the masthead is a small graphic of a person wearing sunglasses. The main story features a large, bold headline: "'The skies will never be the same.'". To the right of the main column, there is a sidebar with the headline "Ch. 11 may let chain play ball". Further down the page, there is another section with the headline "10% employee and the know of choices-of time limited". At the bottom of the page, there is a large graphic for a Valentine's Day promotion featuring a woman holding a bouquet of flowers.

The image shows the front page of The Gazette newspaper. At the top, there are two columns of news headlines. Below the headlines is the main title "The Gazette" in a large, bold, serif font. Underneath the title is a photograph of a man with a beard and glasses, gesturing with his hands as if speaking. To the right of the photo is a column of text. Further down the page, there is a large, bold headline "Einstein was right" followed by a sub-headline "And here's why it matters". Below this is another column of text. At the bottom of the page, there is a small photo booth advertisement with the text "Get Printed Photo Strip Delivery your Valentine's PhotoBooth" and several small photos of people.

# The Bakersfield Californian

FRIDAY, FEBRUARY 12, 2016 • BAKERSFIELD.COM

ADVERTISING 26 • CLASSICS 26 • EYE STREET 26 • ENTERTAINMENT 26 • FEATURES 26 • GARDENING 26 • HOME & GARDEN 26 • INSIDE 26 • LIFE 26 • LOVING 26 • OUTDOORS 26 • PICTURES 26 • POLITICS 26 • SPORTS 26 • STYLING 26 • USA TODAY 26 • WEDDINGS 26

The evolution of two black holes – one 29 times more massive than the other – as they merged for the first time by the laser-interferometer gravitational-wave observatory LIGO. The event, which occurred at a distance of more than 1.3 billion light-years from Earth, was the most powerful ever detected by LIGO. It was also the first time gravitational waves were detected in space and time, corroborating Albert Einstein's century-old theory of relativity.

Credit: LIGO/Caltech/MIT

# MAKING WAVES

## Lawsuit disputes union access to farms

Practice violates "constitutional protection, challenge fails. Successful, yet costly legal efforts by United Farm Workers to connect with ag laborers.

LOCAL 12

At Democratic debate, Sanders, Clinton spur overplay for change

USA TODAY | 20

Illustrated 'Deadpool' starring Ryan Reynolds, wins at the shadow end

USA TODAY | 20

Bakersfield High captures 19th straight

Gravitational waves, that is: New scientific observation affirms Einstein's general theory of relativity

USA TODAY | 30

# The Huntsville Times

## UAH 'AT THE CENTER' OF CONFIRMING EINSTEIN'S THEORY OF RELATIVITY



Lawmakers hold key to building mega-prisons

CONGRESSMAN'S PLAN WORKS

Huntsville ready to welcome Uber, Lyft and Zipcar

Cities have

more sharing services

new car

old school

commutes

Mathematics

middle school

high school

university

postsecondary

adult

work

travel

vacation

leisure

recreation

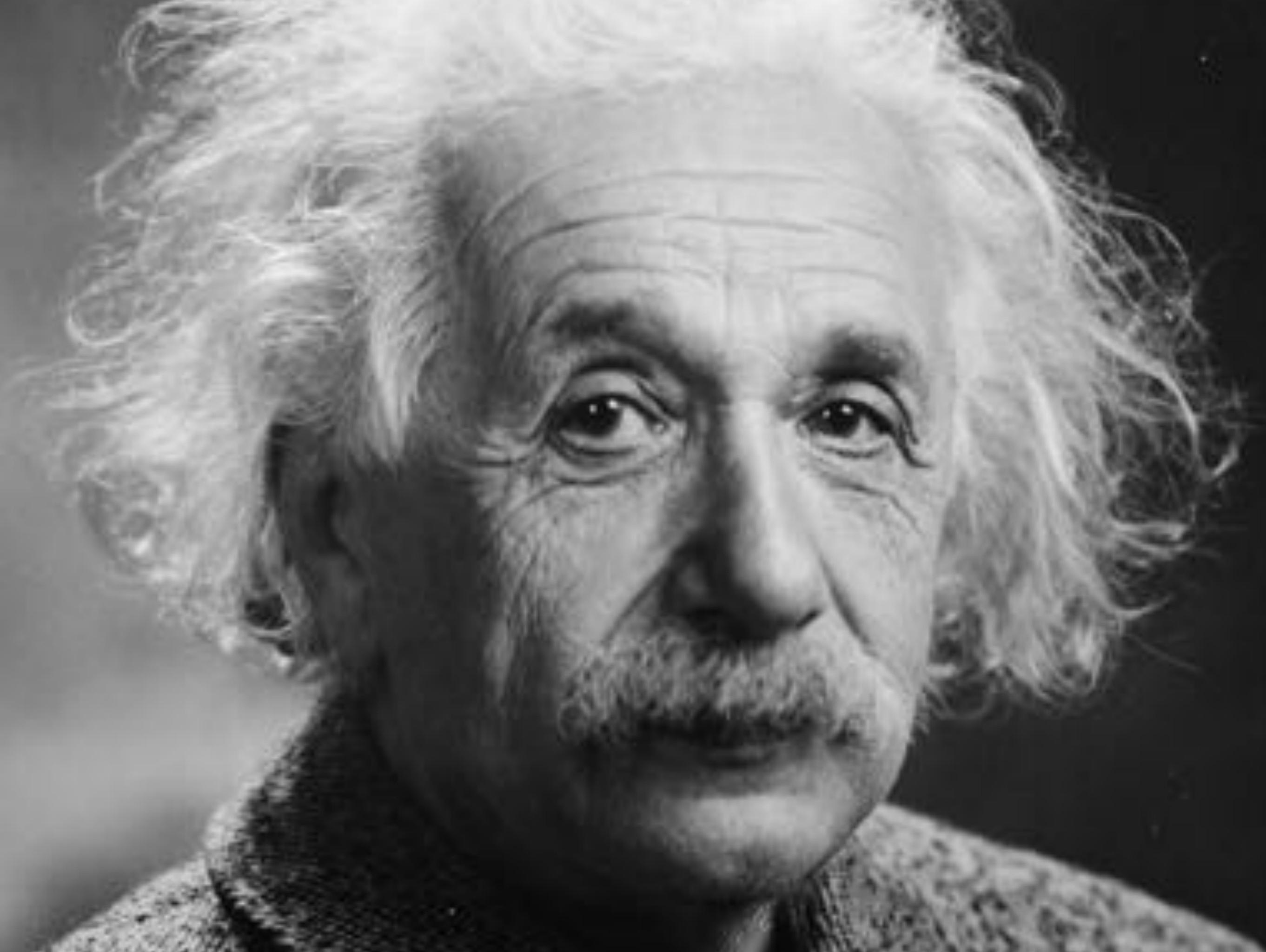
leisure

travel

vacation

leisure

travel

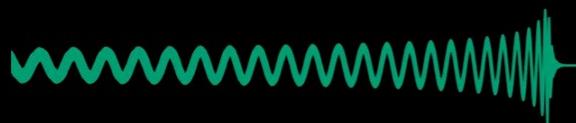




GW150914



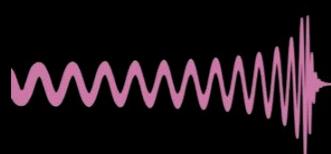
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GW151226



GW170104



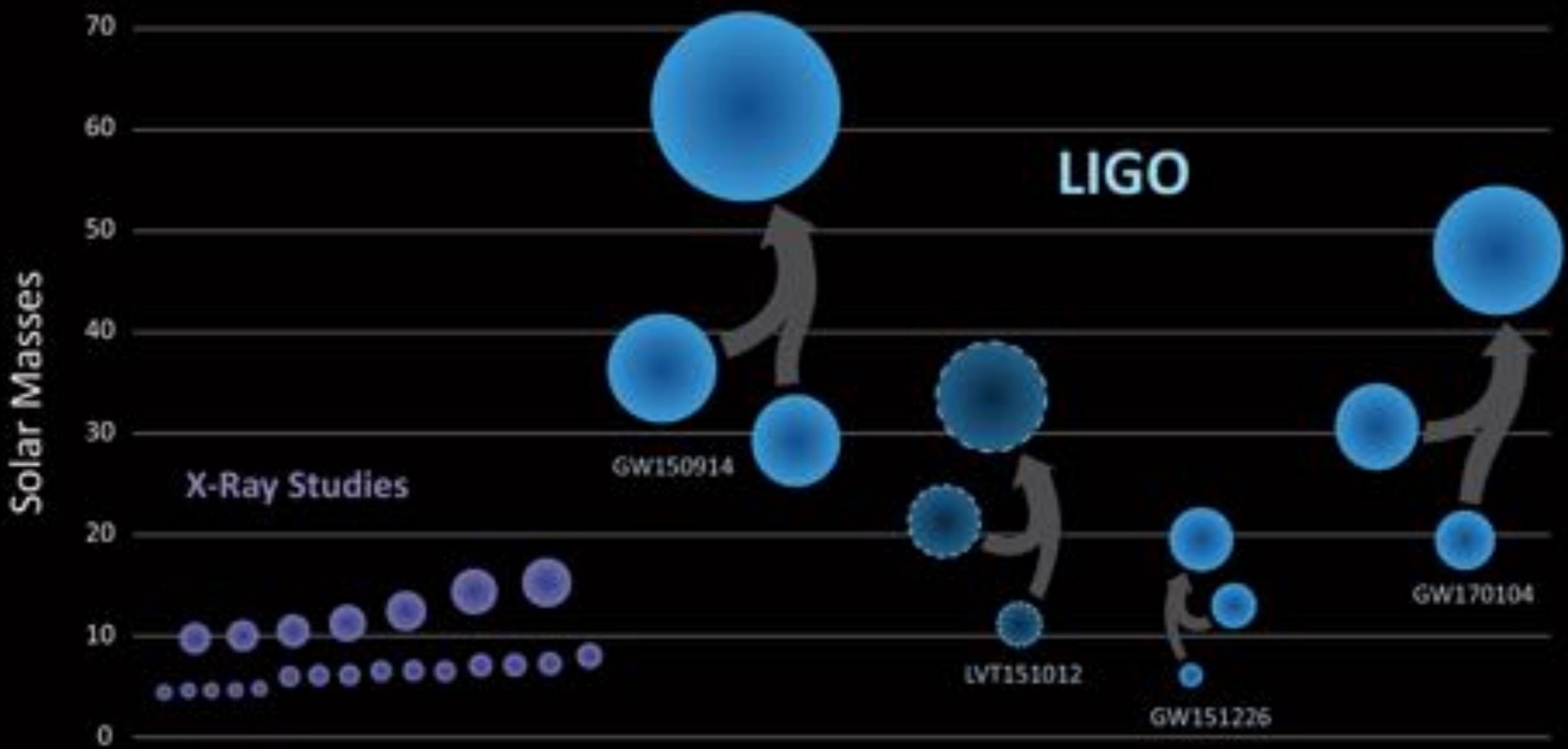
0 sec.

1 sec.

2 sec.

time observable by LIGO

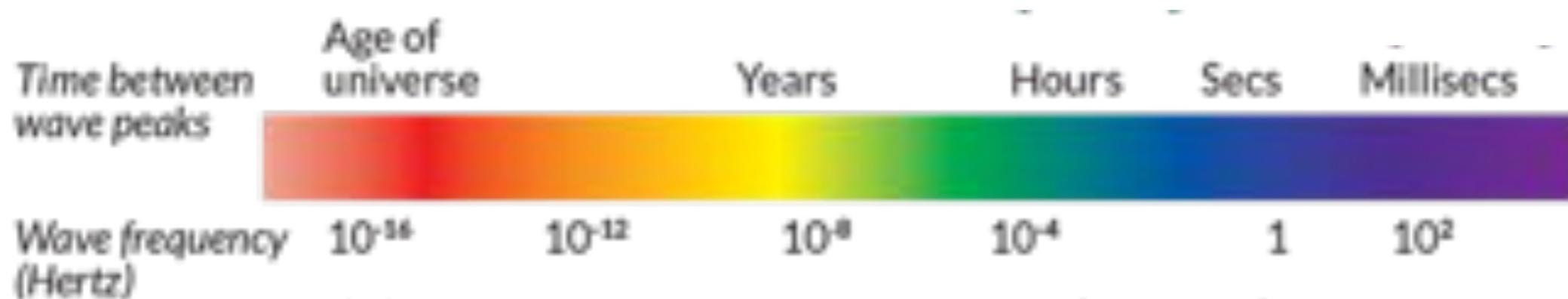
# Black Holes of Known Mass



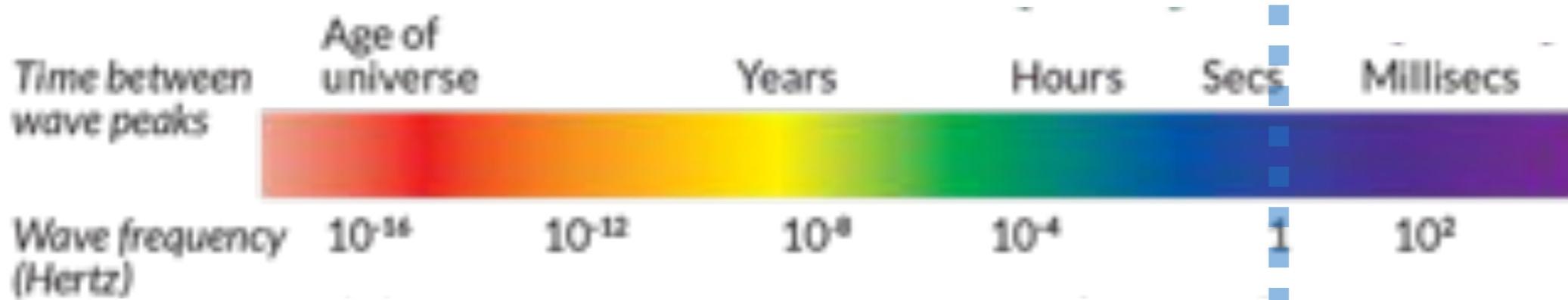


LIGO

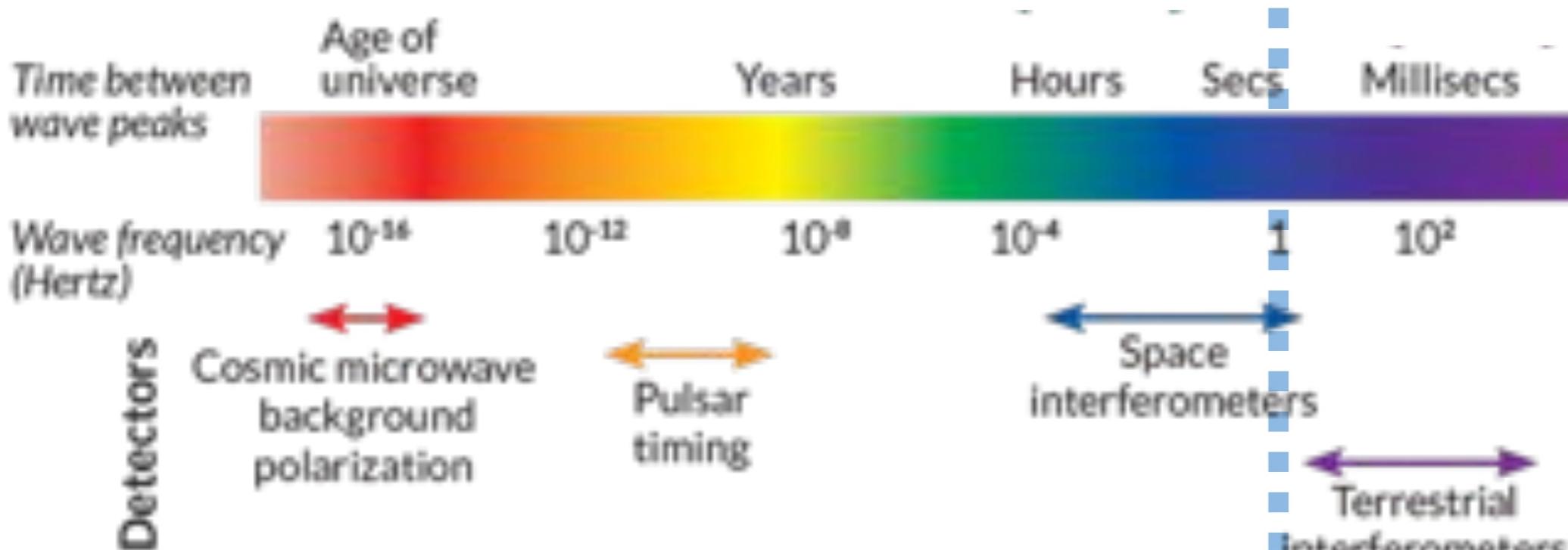


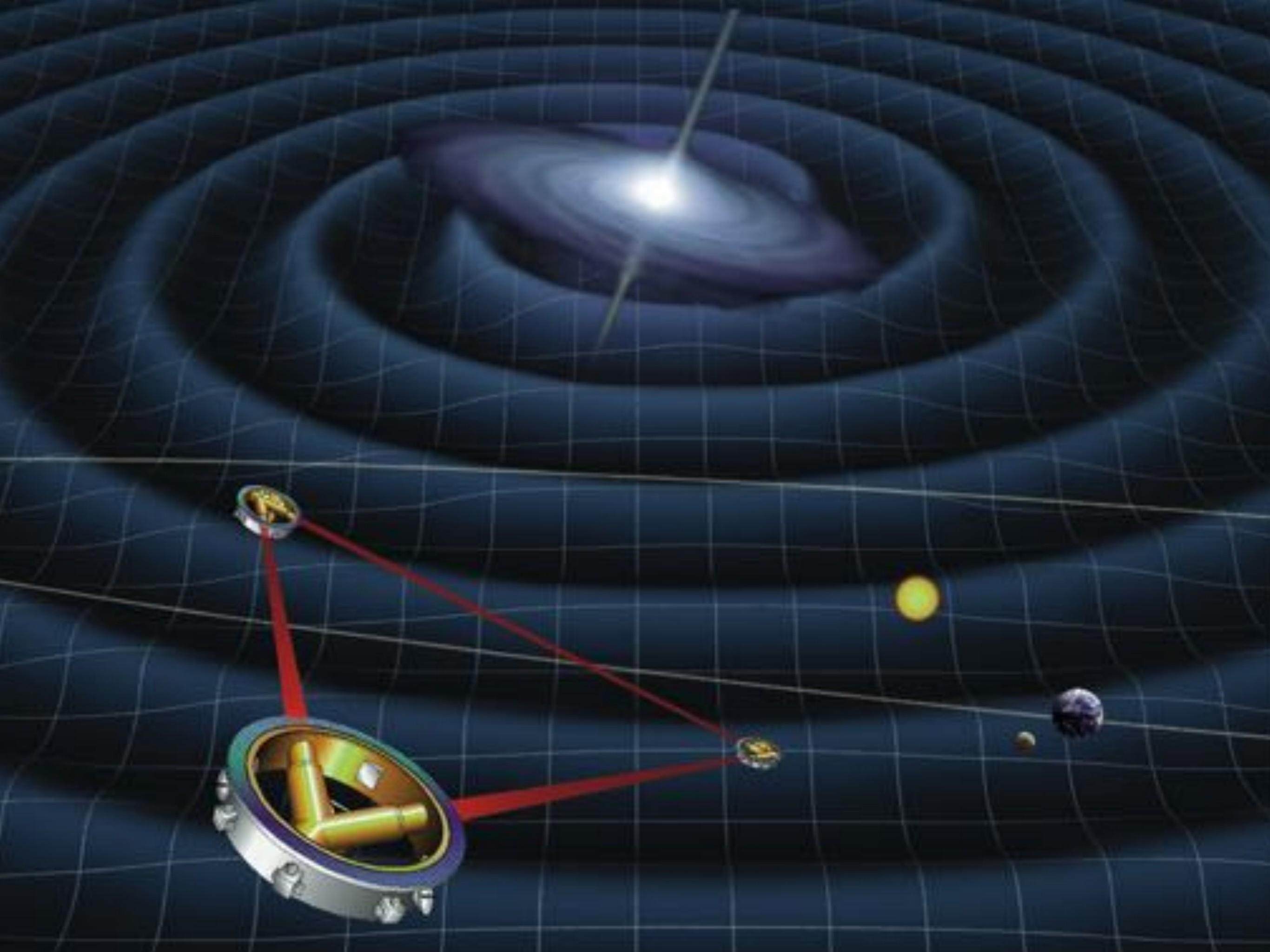


## **Test masses can not be on Earth**



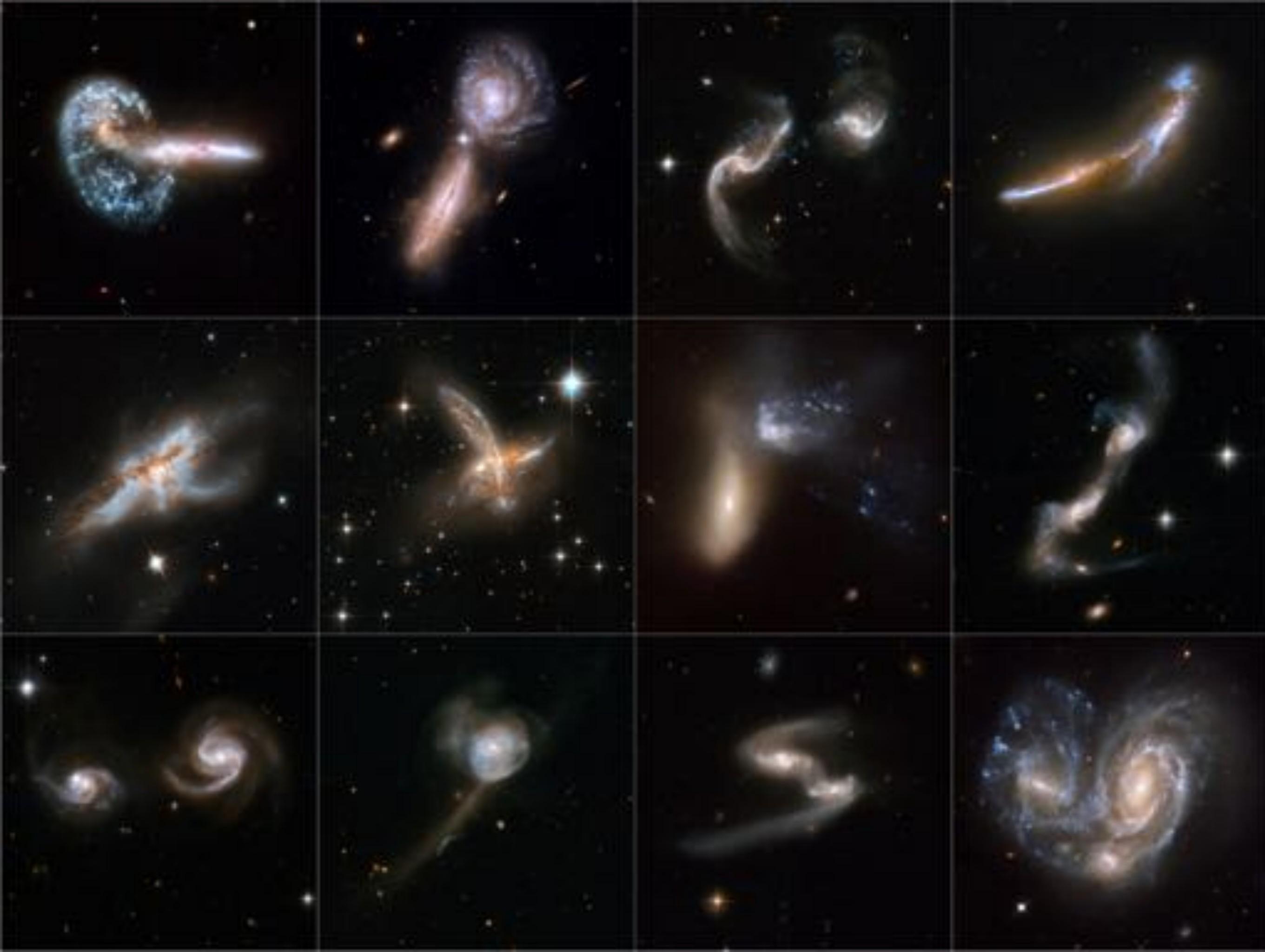
## Test masses can not be on Earth





# LASER INTERFEROMETER SPACE ANTENNA







Large black hole:  
shown to scale  
3,000,000 solar masses  
90% maximal spin

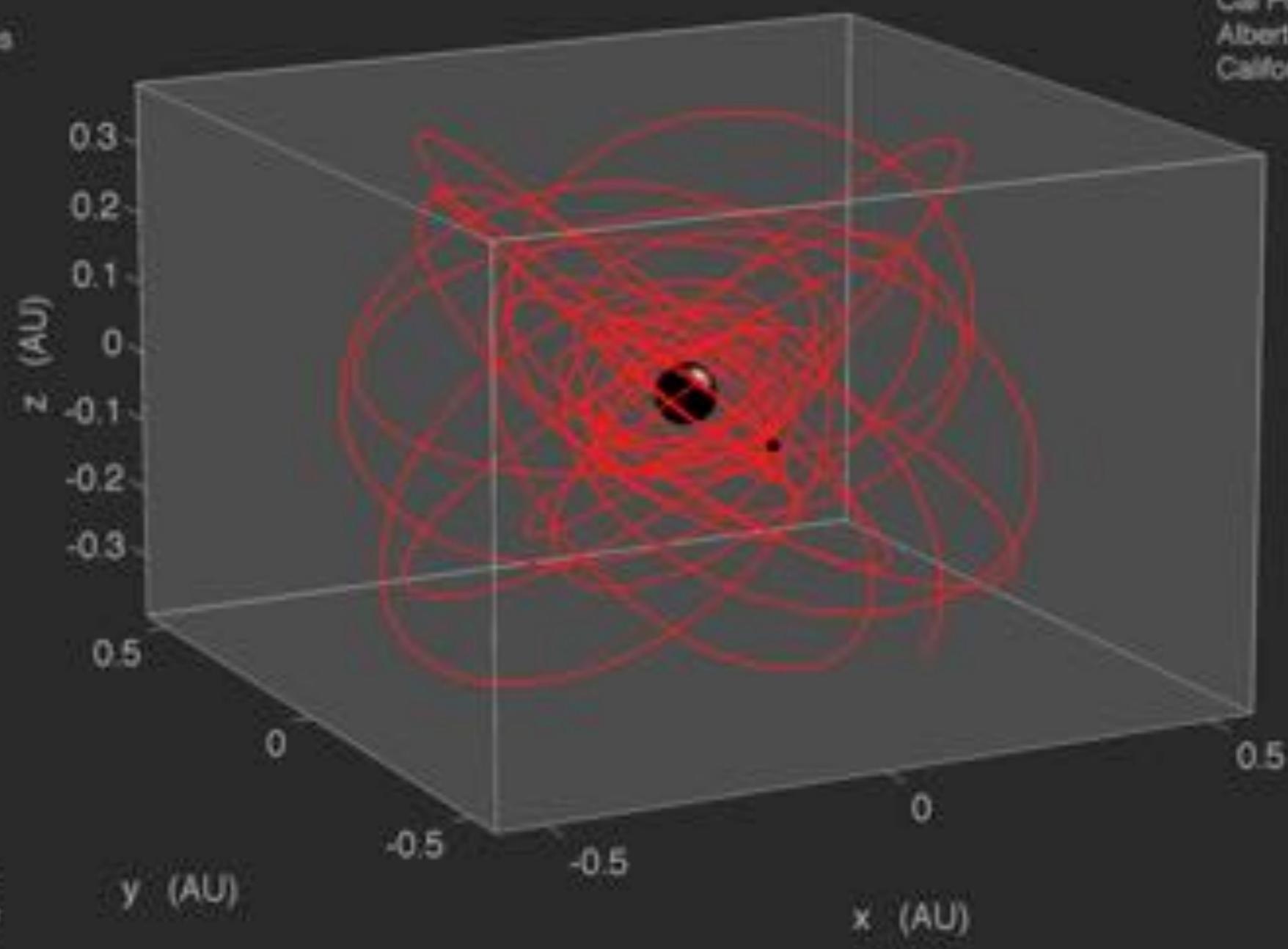
Small black hole:  
shown enlarged  
270 solar masses  
negligible spin

Trace duration  
1 day

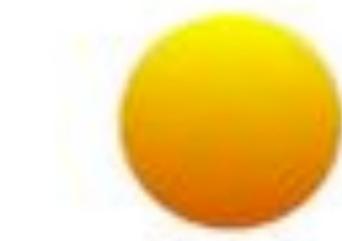
"plus" waveform viewed  
from 45 degrees latitude

100 days before merger, 28% of light speed

Steve Drasco  
Cal Poly, San Luis Obispo  
Albert Einstein Institute  
California Institute of Technology



Scale = 0 kpc



# LISA Pathfinder



Image: ESA/ATG Medialab

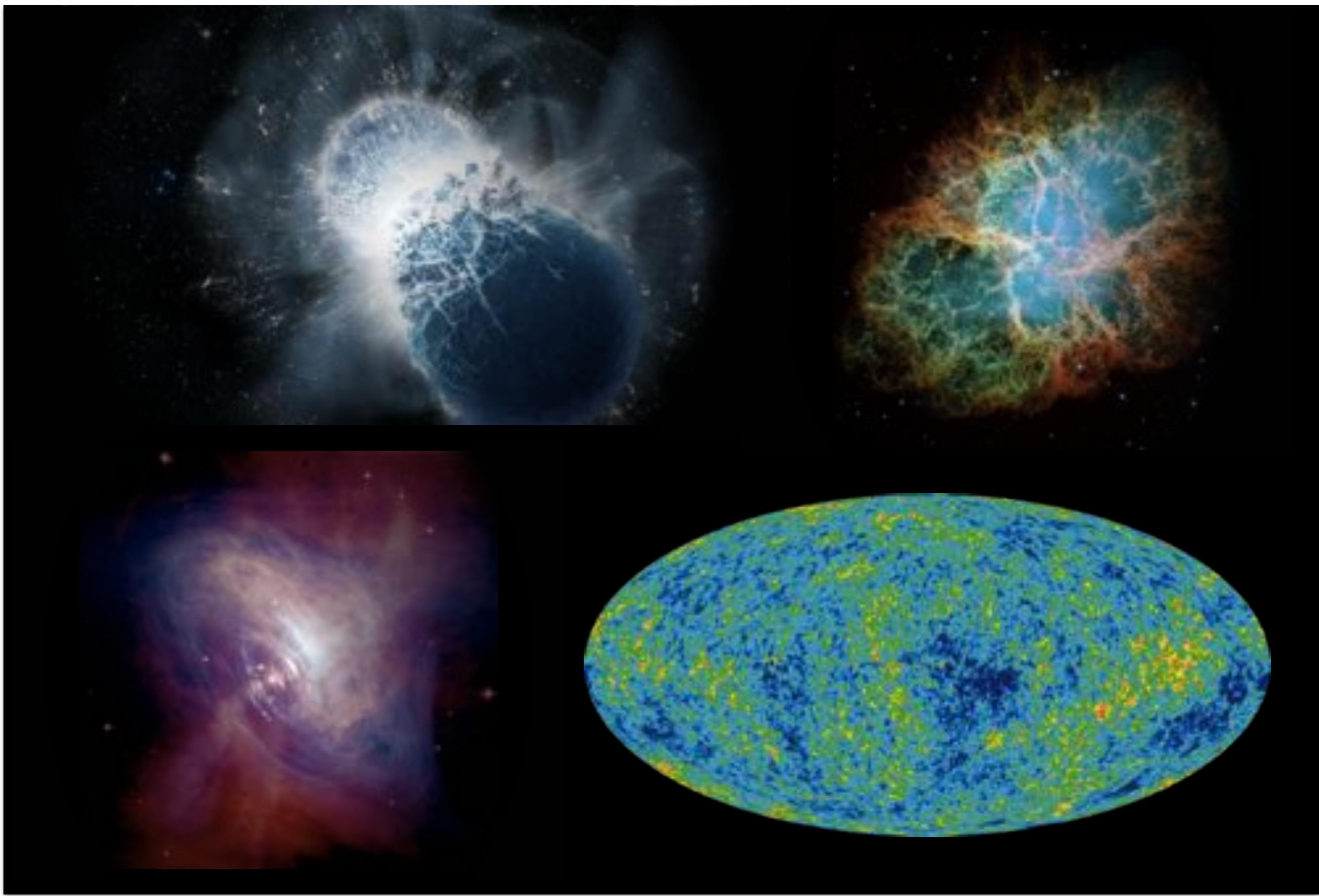


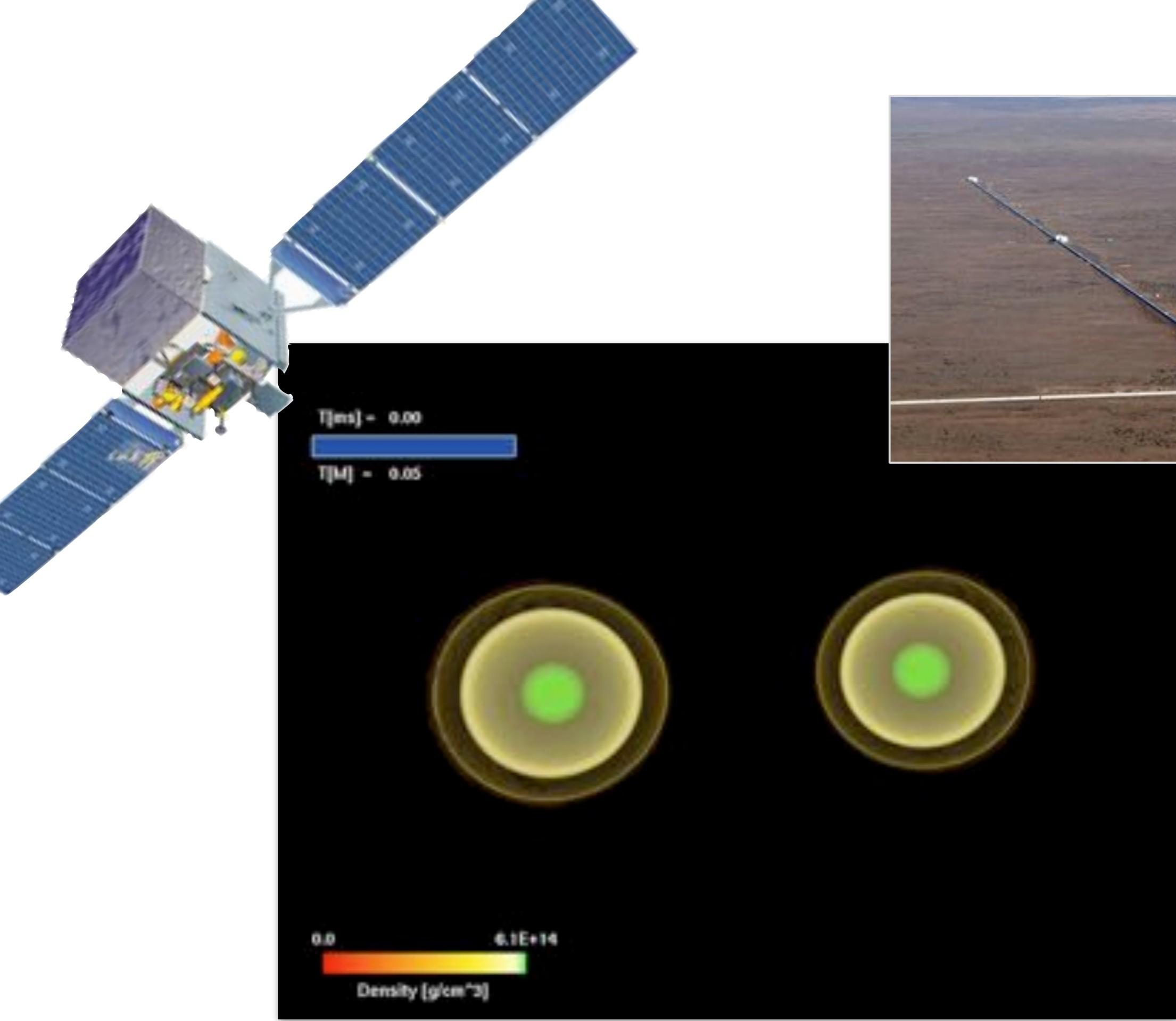
Image: ESA

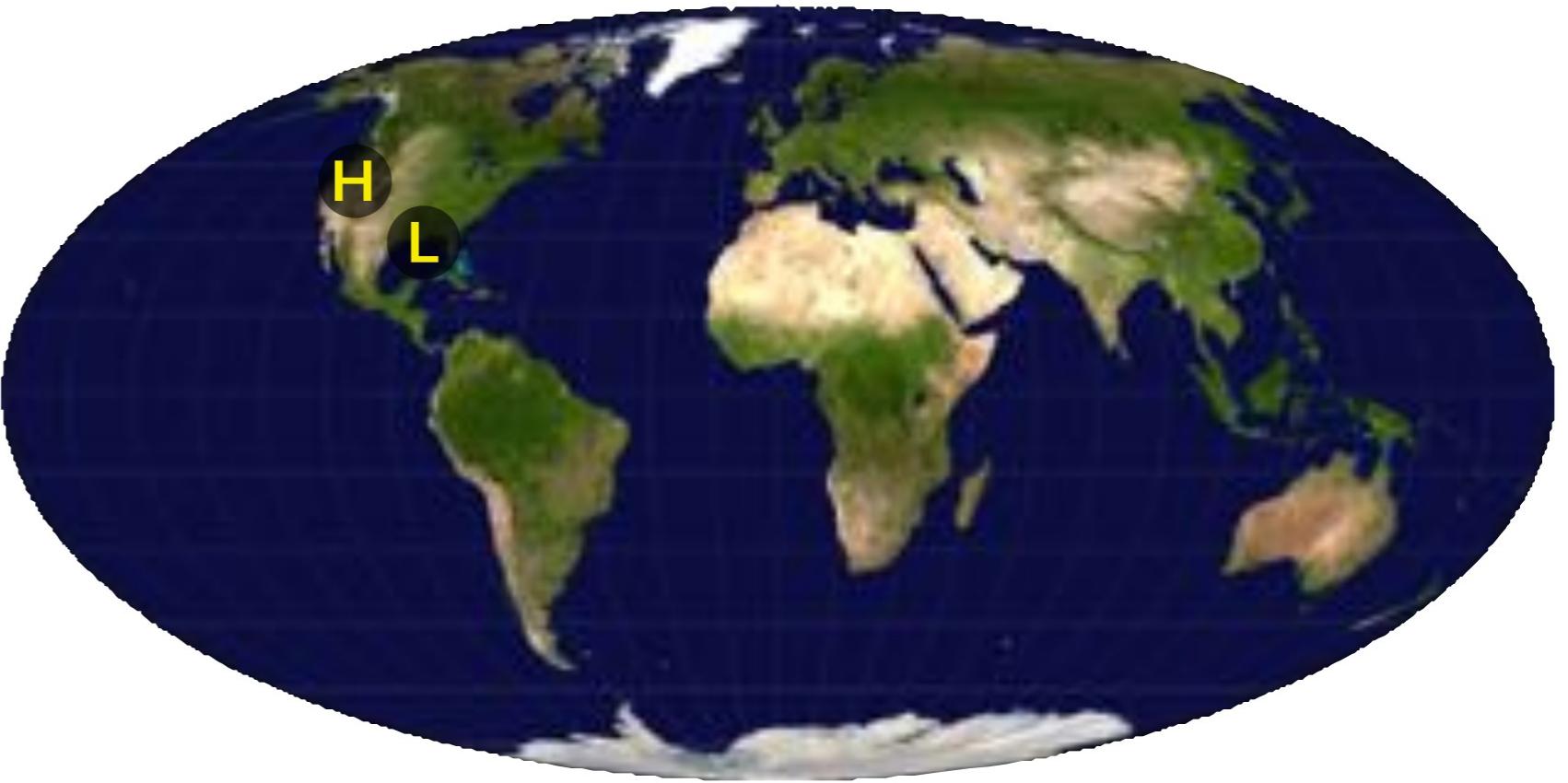


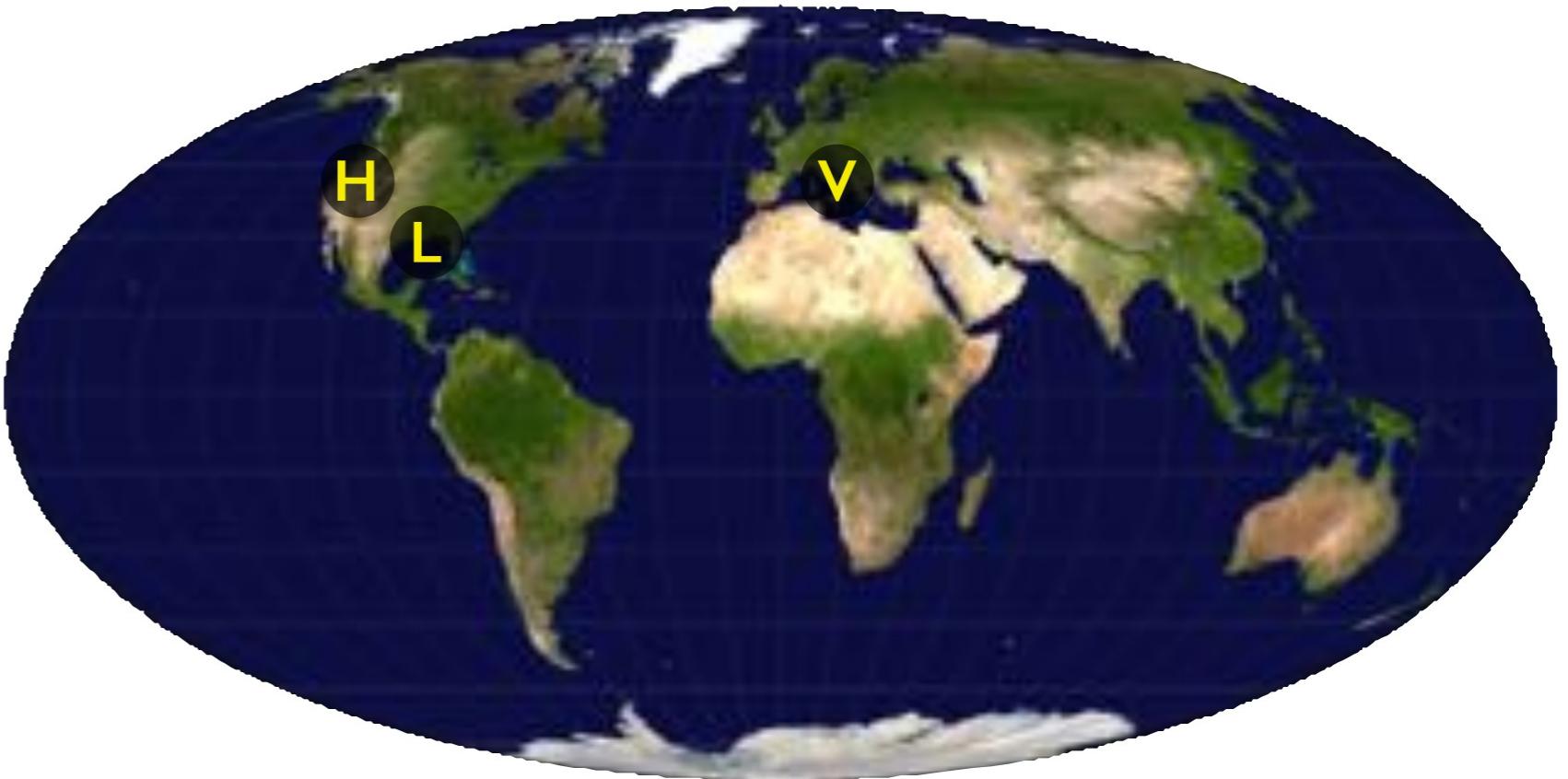
Image: ESA

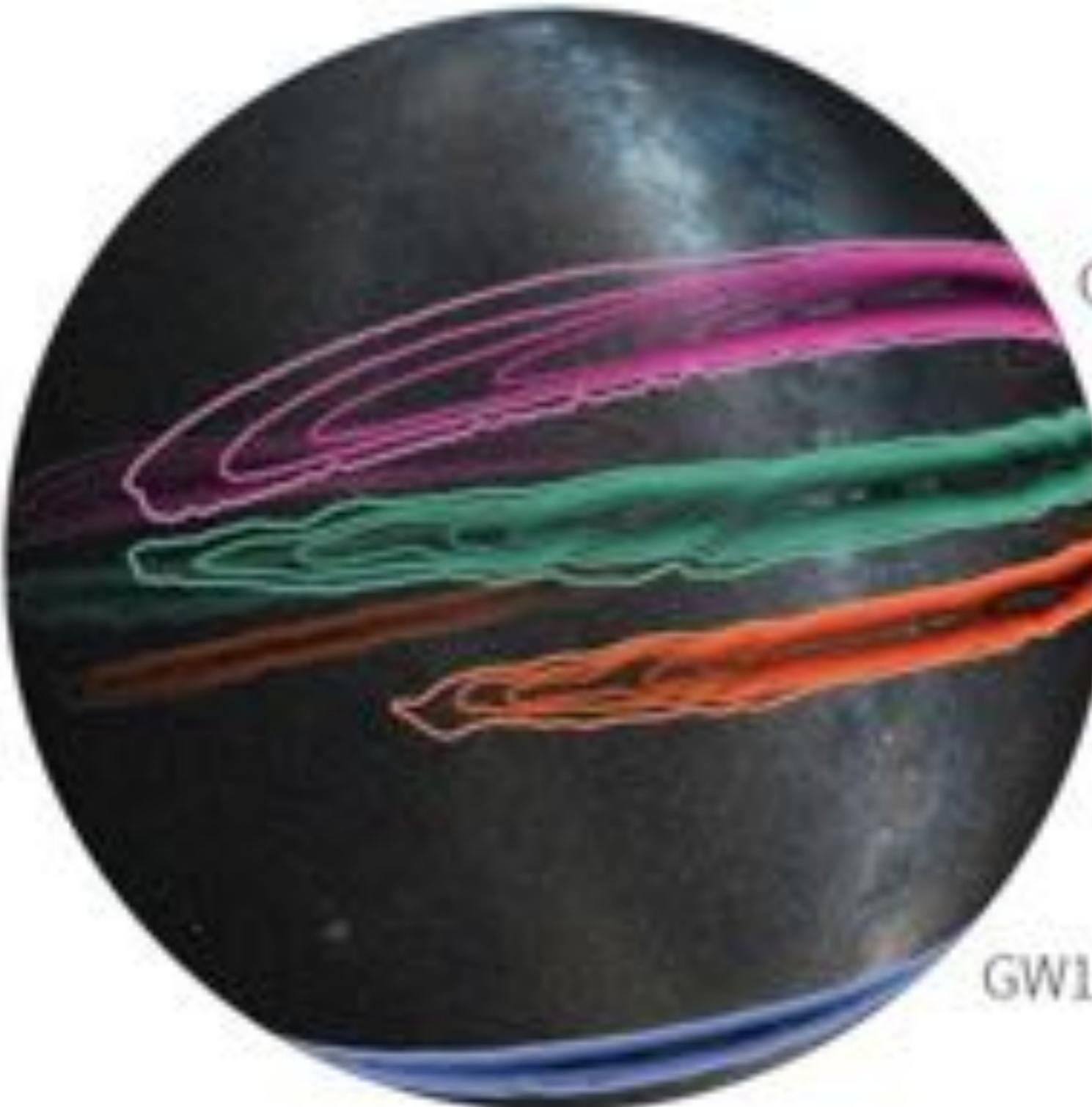










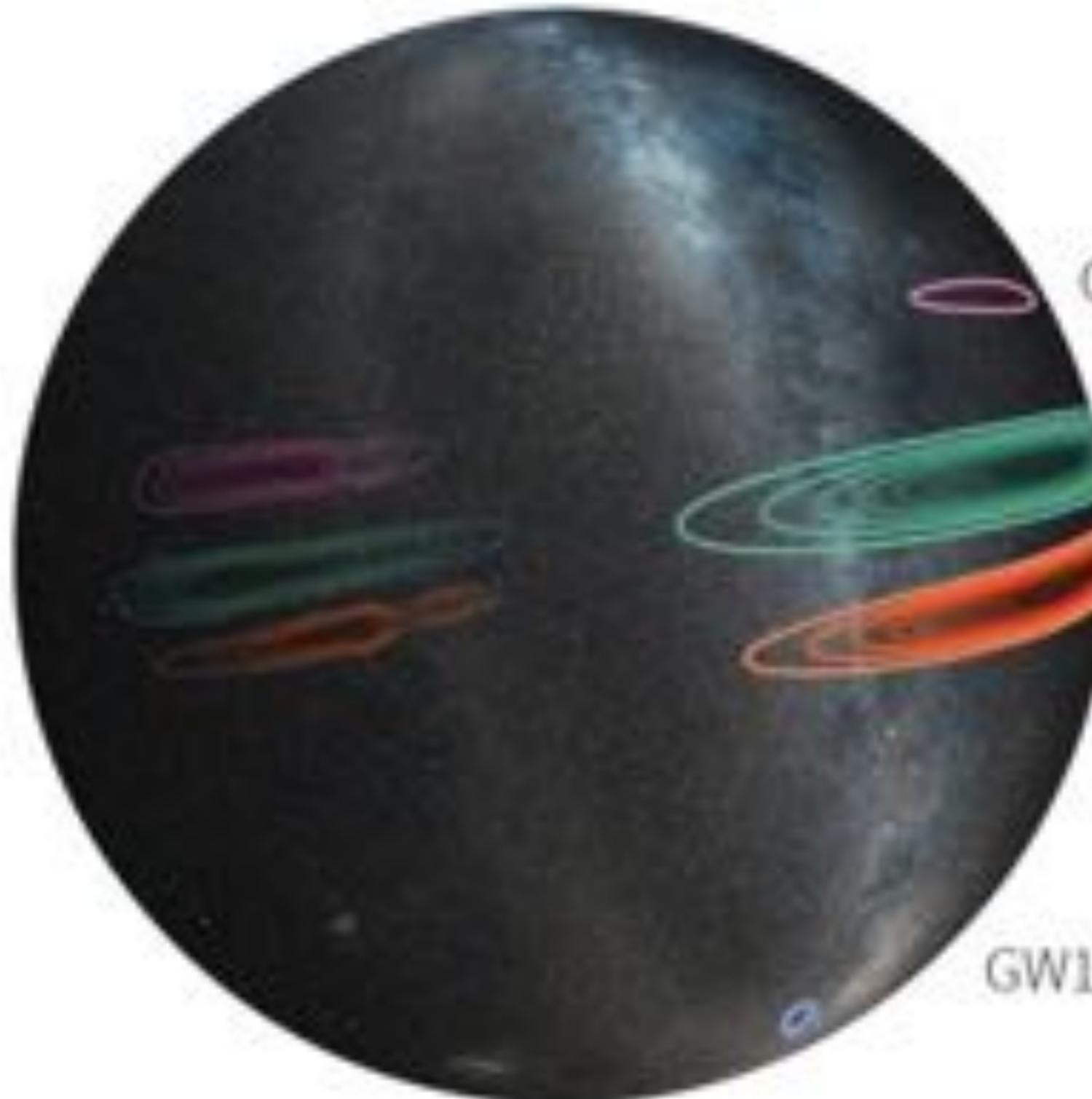


GW170104

LVT151012

GW151226

GW150914

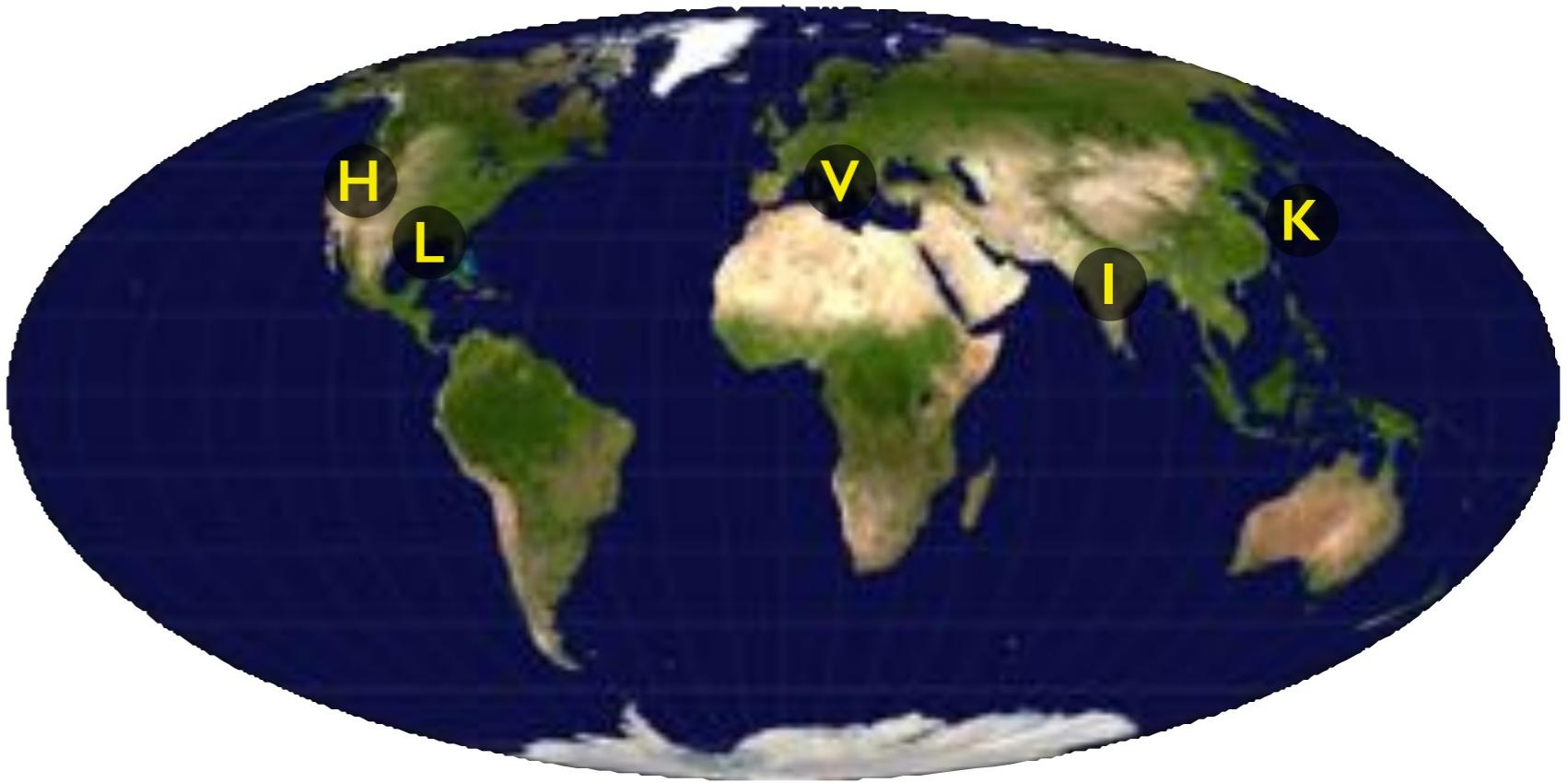


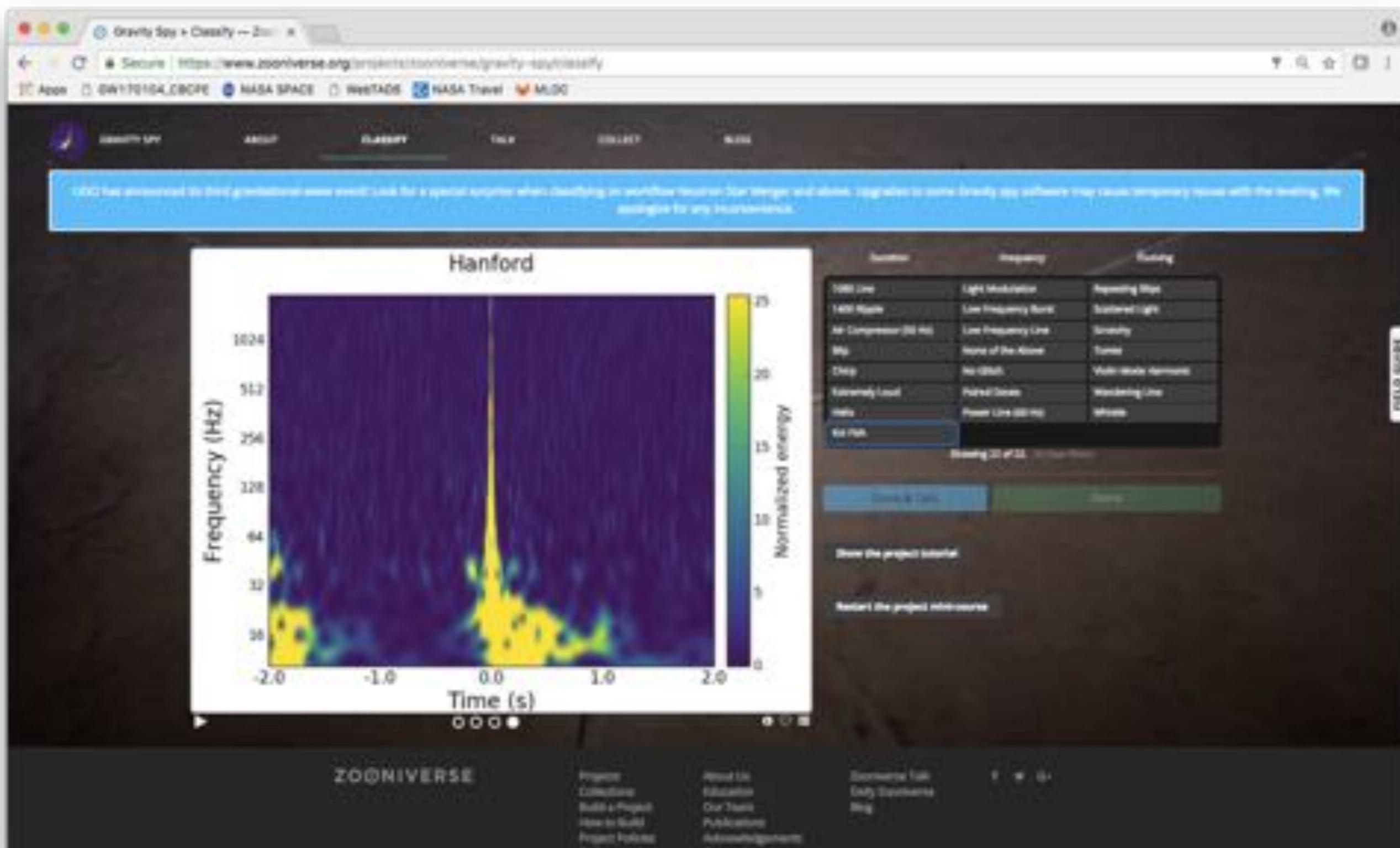
GW170104 +VIRGO

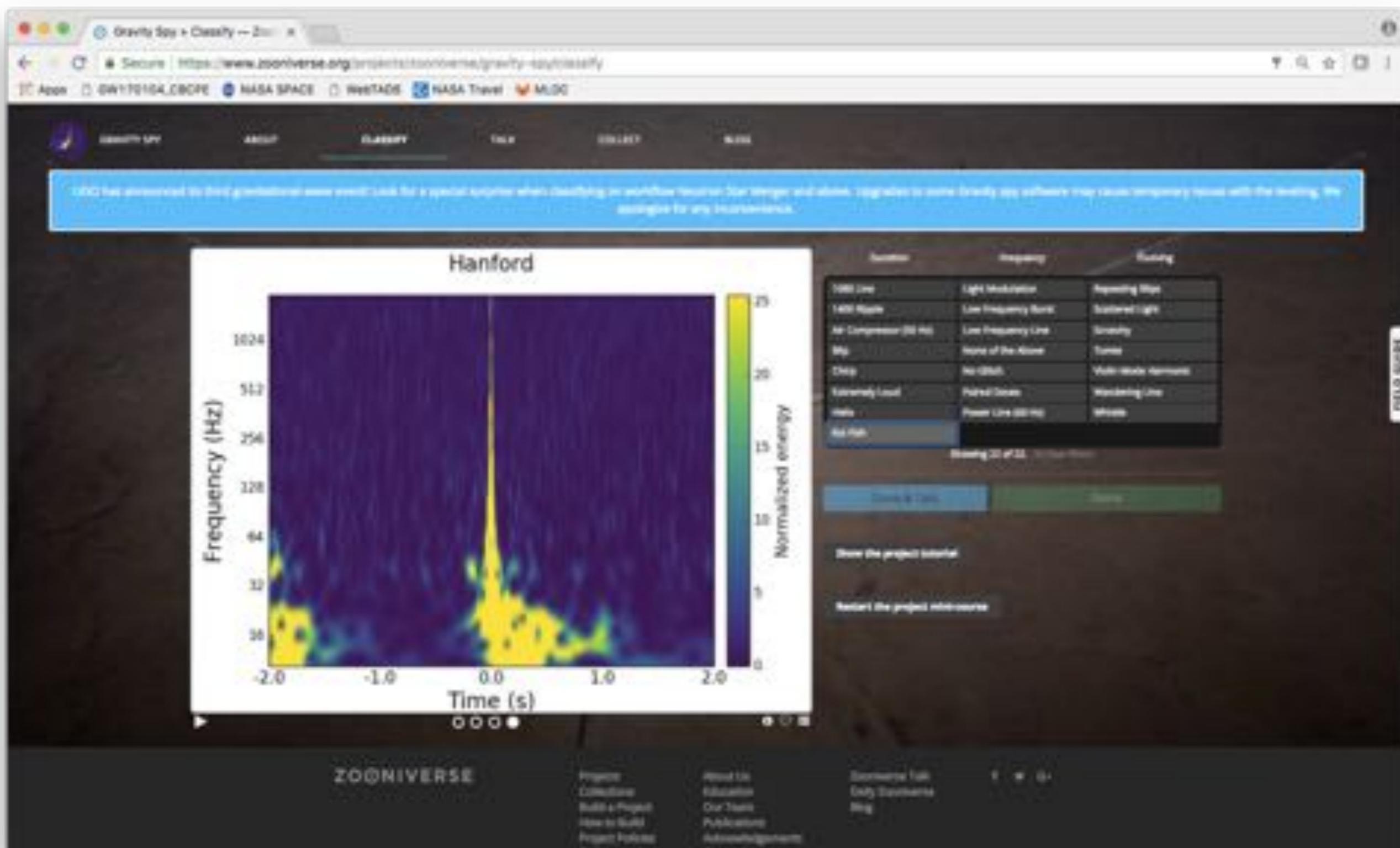
LVT151012 +VIRGO

GW151226 +VIRGO

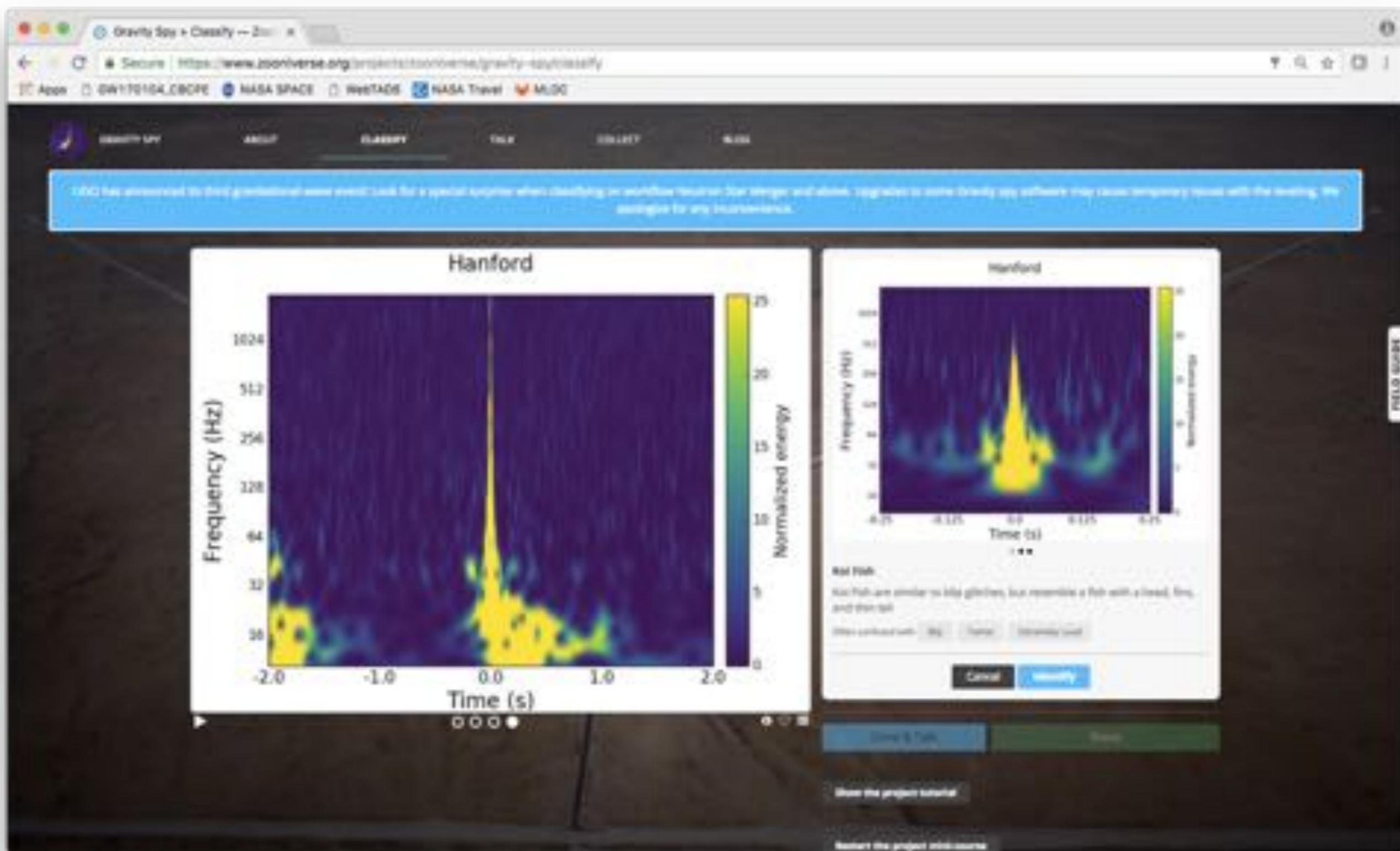
GW150914 +VIRGO



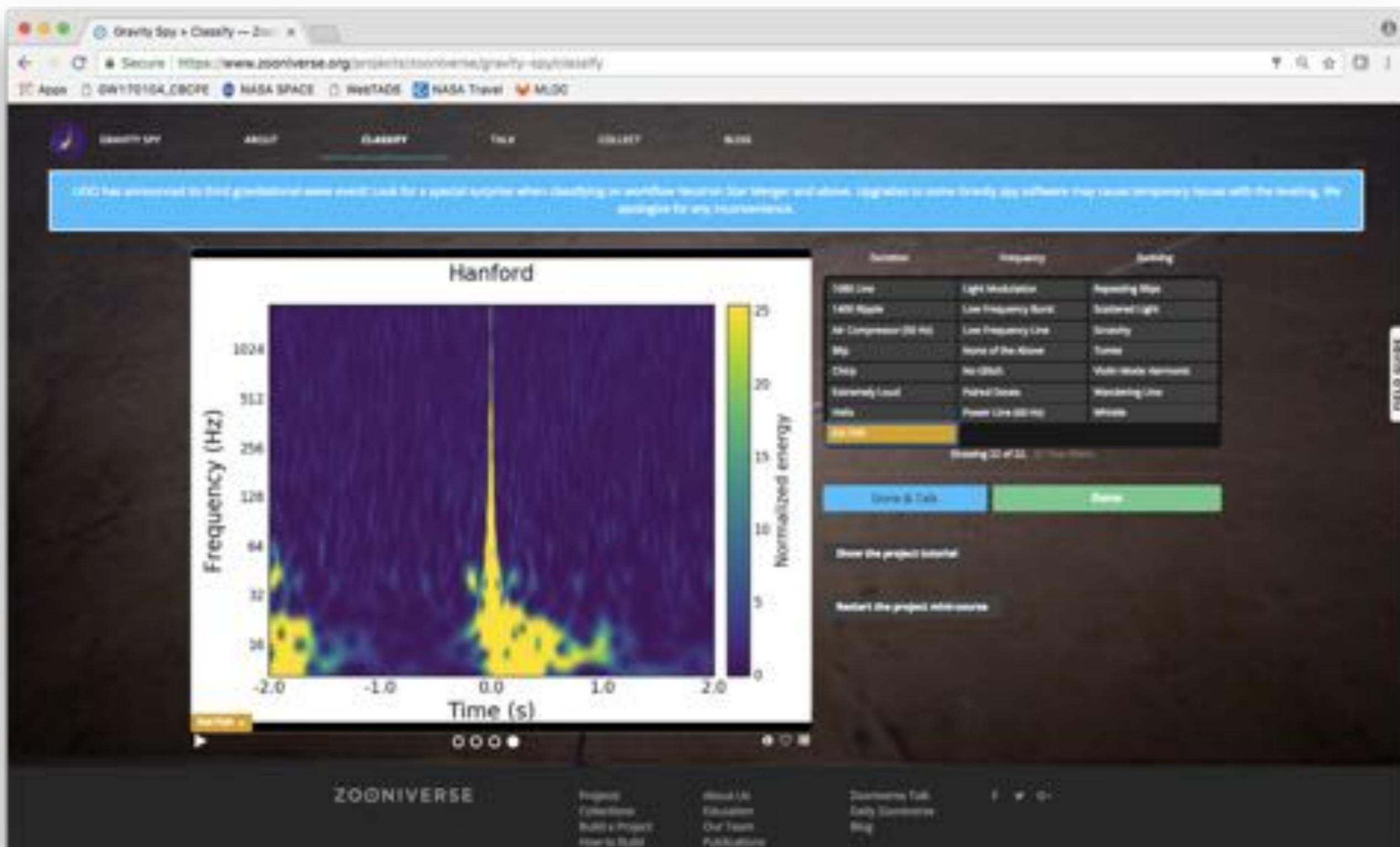


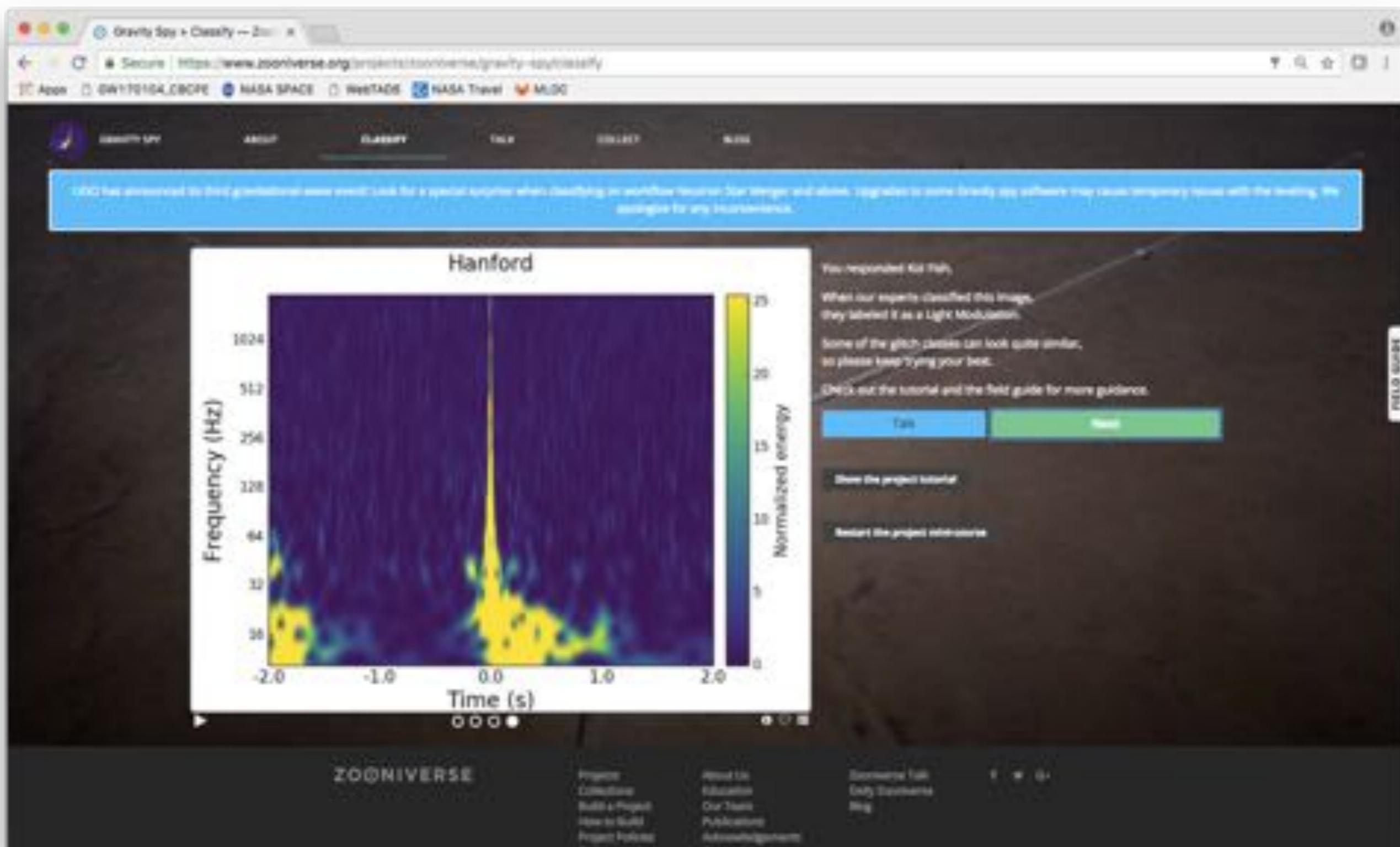


# www.gravityspy.org



# www.gravityspy.org





# www.gravityspy.org

Gravity Spy - Talk — Zooniverse

Secure | https://www.zooniverse.org/projects/zooniverse/gravity-spy/talk

Apps GW170814\_CBOPE NASA SPACE WestAOIS NASA Travel MLDC

## Gravity Spy Talk

Search or enter a tag

**Notes**  
General comment threads about individual subjects  
 gravityspyclub Subject 1642287 16 hours ago

**Bug reports**  
A place to report technical bugs in the project  
 gravityspyclub Problem in the no glitch example 16 hours ago

**Chat**  
A place for general discussion about Gravity Spy or anything else you want to talk about  
 anotheruser Too many tag categories

**Help**  
A place to ask questions about the classification interface and get general help about the Gravity Spy site  
 anotheruser Already seen? 2 days ago

**Science**  
A place to talk about the science behind Gravity Spy and related research  
 gravityspyclub Background Noise Patterns 2 days ago

**Collections**  
A place to introduce, discuss, and collaborate on your collections  
 anonymous Painted Doves Testing 12 days ago

**New Glitch Classes**  
Announcing new, permanent classes of glitches that will eventually be incorporated into the project  
 anonymous Thread placeholder to prevent problems with Talk Homepage 1 months ago

**Recent Comments**  
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Kit  
1600px  
990  
zooniverse  
2019  
By  
1000px  
Background  
noise  
Glitch  
classification  
tutorial  
what  
methodology  
background  
noise  
classification  
tutorials  
background  
noise  
**3 Active Participants:**  
anotheruser, anonymous, 5eCreeper  
**Recent Posts**  
**Projects:**  
Zooniverse.org  
Subjects of the Dark Galaxy  
Socompa Satellites  
Blueshift  
April 2020  
Project Lead Count  
Dataset Features  
ManualMasks  
SelectedFeatures  
The Feature

# Gravitational Wave Astronomy

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Tyson B. Littenberg

NASA/Marshall Space Flight Center

